Acknowledgements:
The E158, HAPPEX, PREX & MOLLER collaborations

Parity-Violating Electron Scattering: MeV to TeV Physics

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University of Massachusetts, Amherst

Nuclear Science Division Colloquium
Lawrence Berkeley Laboratory
November 16, 2011

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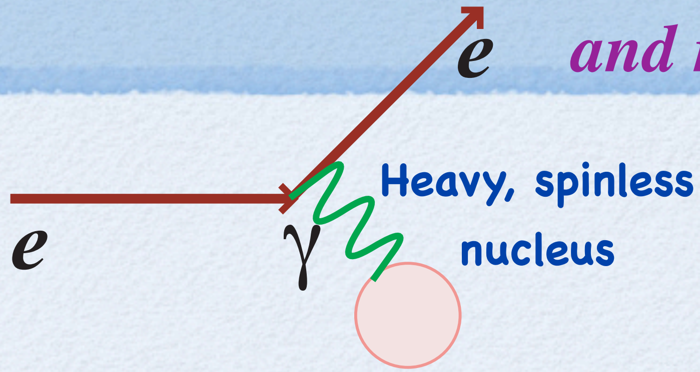
- **Historical Perspective**
  - Relativistic Electron Scattering and Substructure
  - Parity Violation (PV) in Weak Interactions
  - Neutral Weak Interactions
  - PV in Electron Scattering
- **PV in Elastic Electron Scattering and Hadron Structure**
  - Strangeness in the Nucleon
    - New result from HAPPEXIII at Jefferson Laboratory
  - The Neutron Skin of a Heavy Nucleus
    - New Result from PREX at Jefferson Laboratory
- **PV Electron Scattering and TeV-Scale Physics Searches**
  - Past results, and ongoing and future initiatives
- **PV Observables at an Electron Ion Collider**
  - New Spin Structure Functions

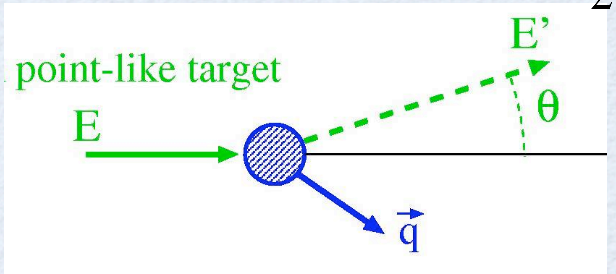
Historical Perspective

Relativistic Electron Scattering

and nuclear substructure



4-momentum transfer $q^2 = -4EE'\sin^2\frac{\theta}{2}$



Q^2: -(4-momentum)^2 of the virtual photon

$$Q \approx \frac{hc}{\lambda}$$

Differential Cross Section

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \frac{4Z^2\alpha^2E^2}{q^4}$$

Relativistic Electron Scattering

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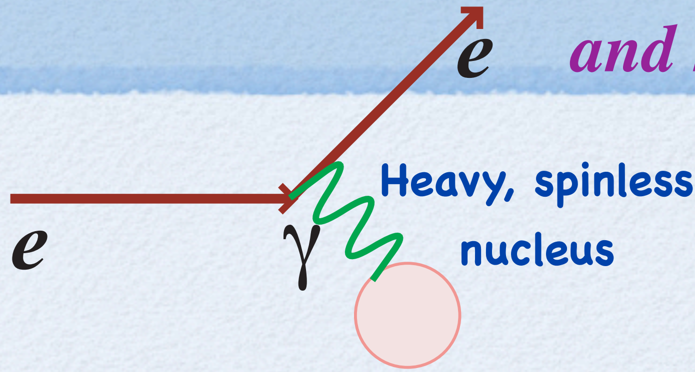

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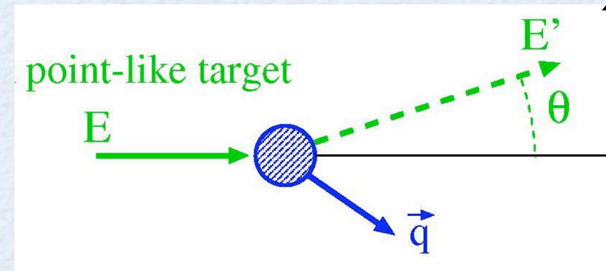

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As Q increases, nuclear size modifies formula

$$F(q) = \int e^{iqr}\rho(r)d^3r$$

Neglecting recoil, form factor is the Fourier transform of charge distribution

Relativistic Electron Scattering

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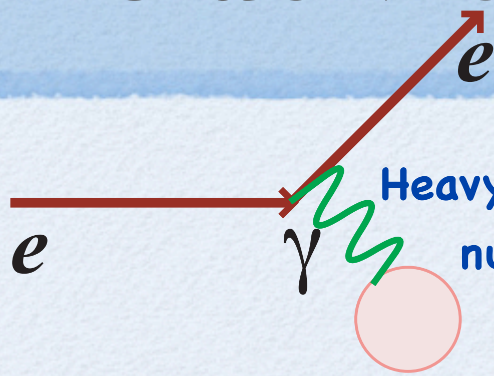

Heavy, spinless nucleus

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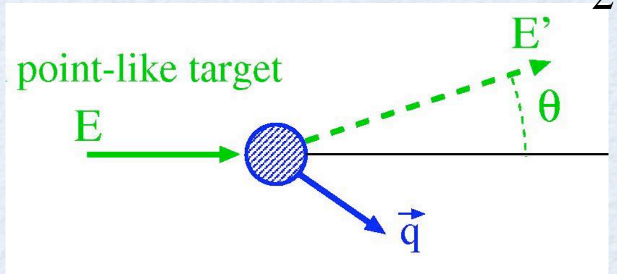

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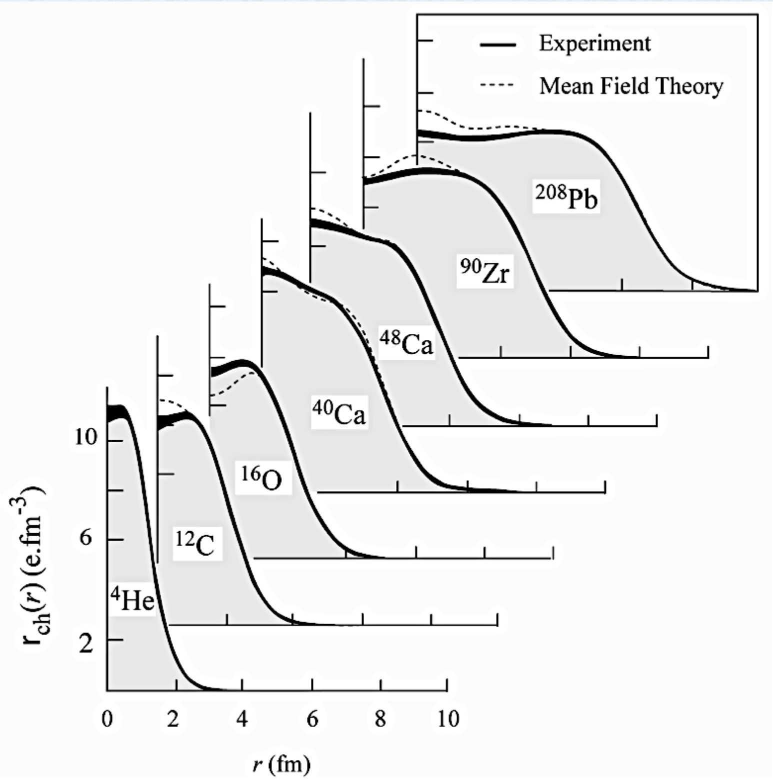

Relativistic Electron Scattering

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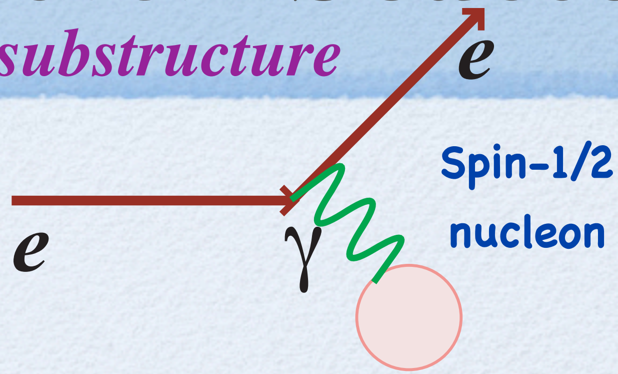

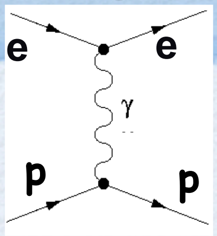

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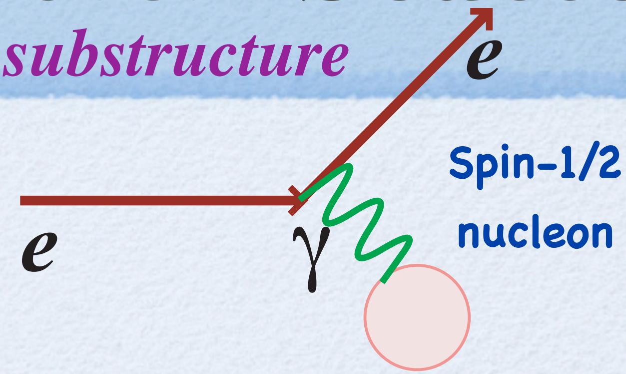

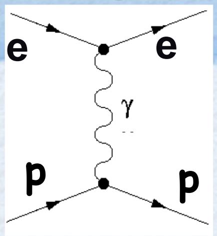

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If proton is not point-like: ***The electric and magnetic form factors G_E and G_M parameterize proton substructure.***

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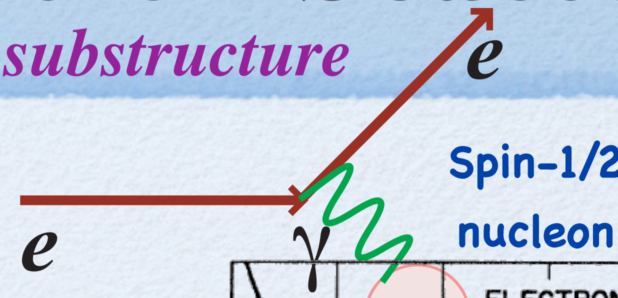

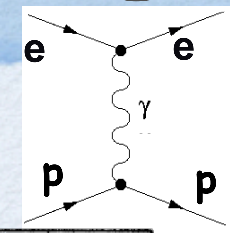

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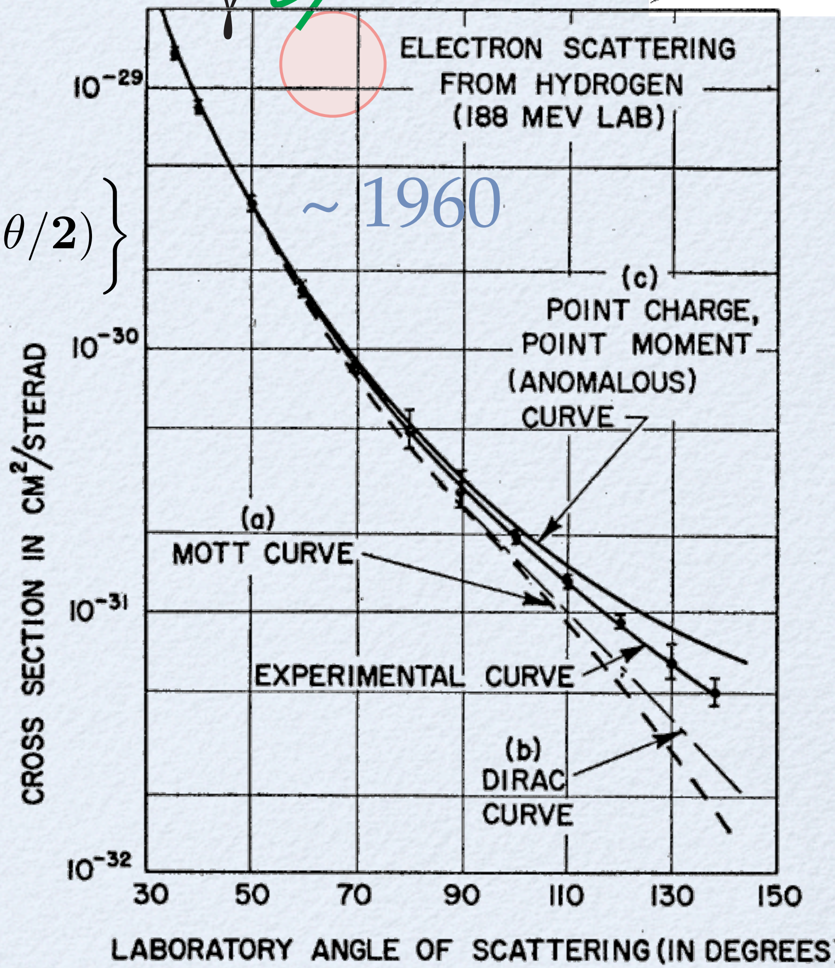

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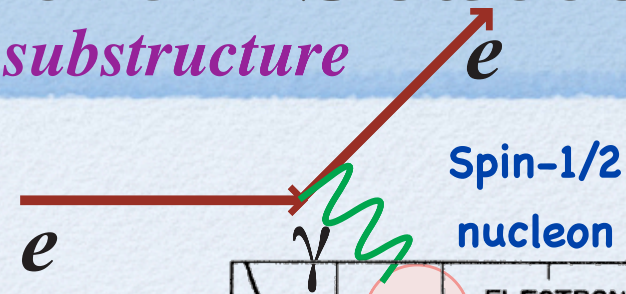

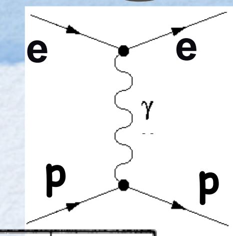

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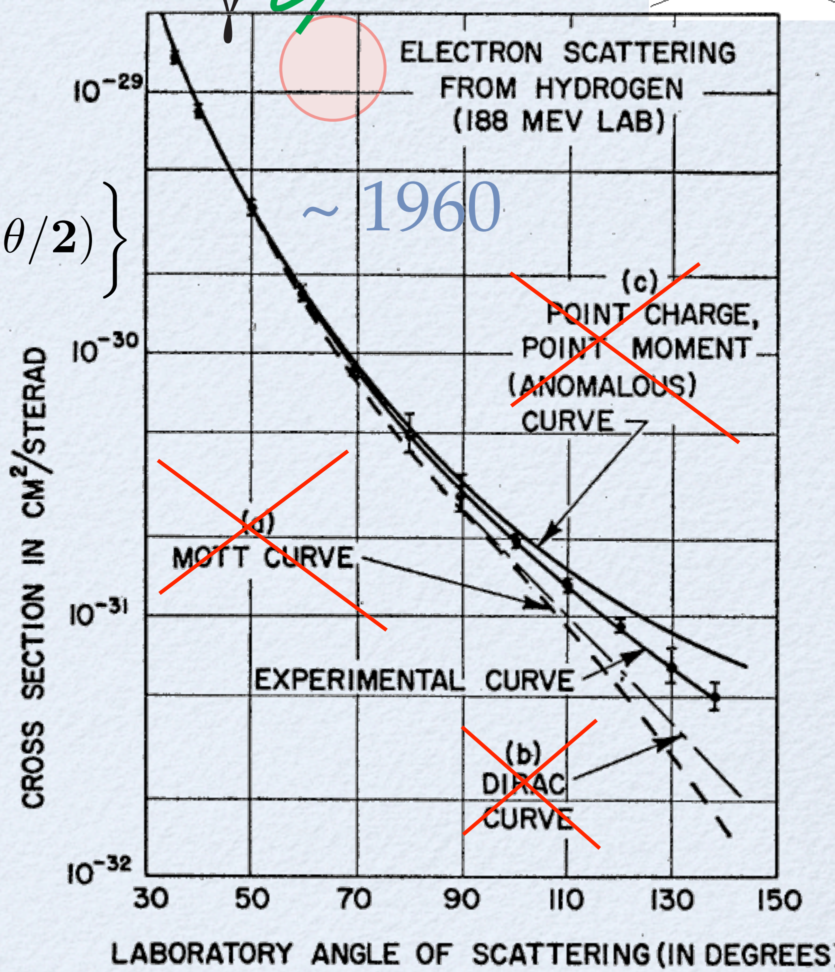

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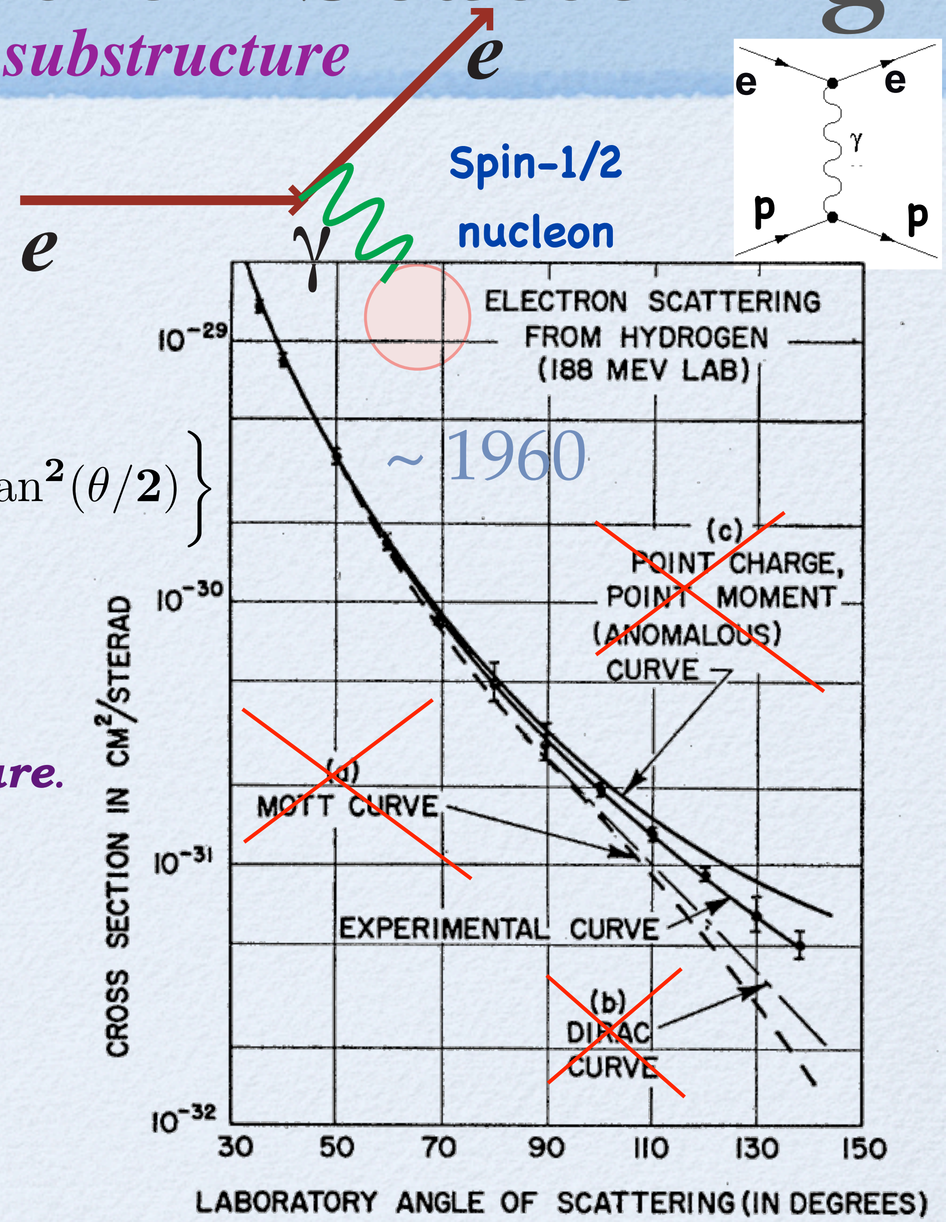

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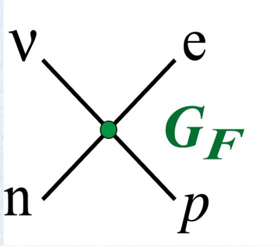
the proton has finite size

Weak Interactions

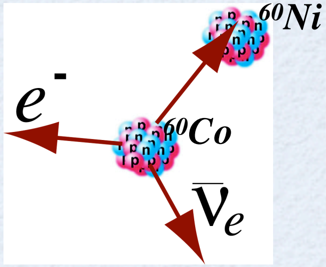
Neutron & nuclear β Decay



Fermi Theory for weak interactions

Universal strength: coupling constant G_F

"Effective" low energy theory that explains many observed properties of radioactive nuclear decays

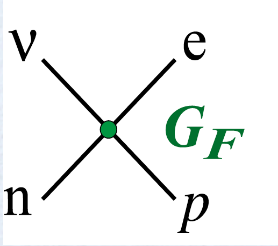


Weak decay of ^{60}Co Nucleus

Weak Interactions

Observed NOT to be invariant under parity transformations

Neutron & nuclear β Decay



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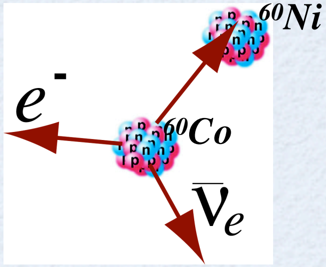
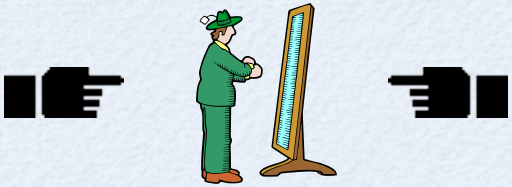


Weak decay of ^{60}Co Nucleus

parity transformation (reflection)

$$x, y, z \to -x, -y, -z$$



$$\vec{p} = -\vec{p}$$

$$\vec{L} = \vec{L}$$

$$\vec{s} = \vec{s}$$

Weak Interactions

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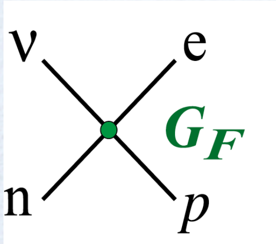
Neutron & nuclear β Decay



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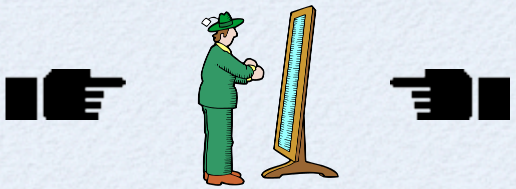

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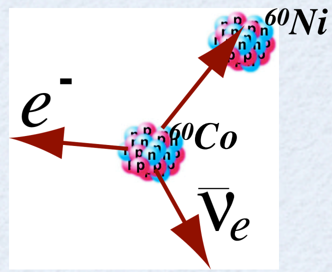

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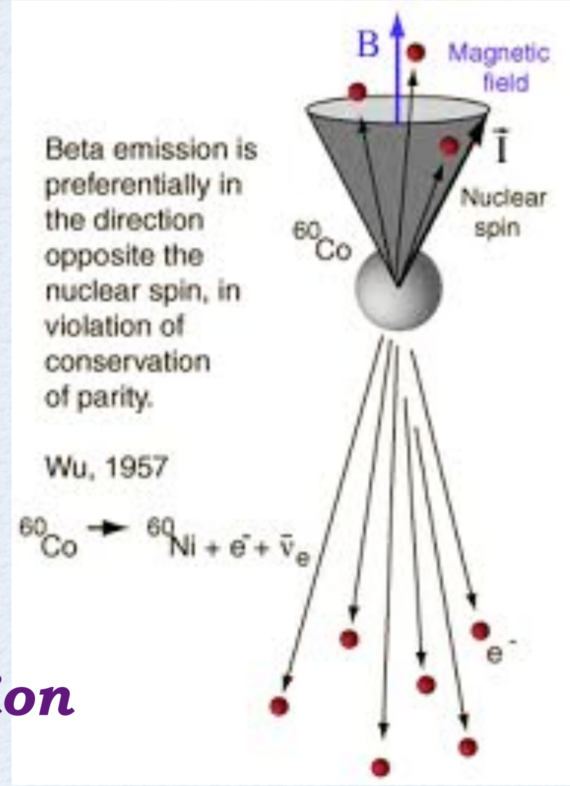


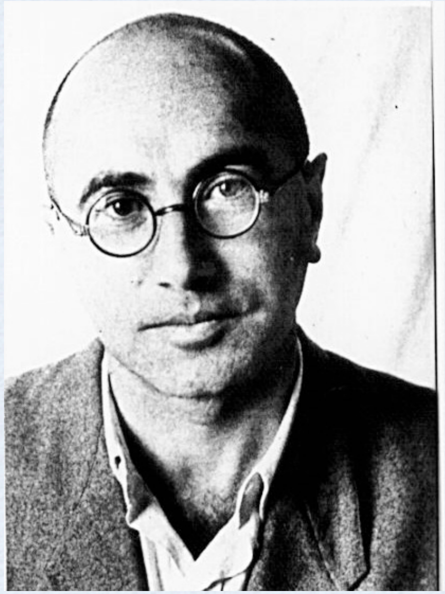
observed anisotropy in beta-emission when nuclei aligned to a magnetic field

1957

signature of parity violation

A Classic Paper

After V-A theory was proposed to explain parity-violation in weak interactions….



LETTERS TO THE EDITOR

PARITY NONCONSERVATION IN THE FIRST ORDER IN THE WEAK-INTERACTION CONSTANT IN ELECTRON SCATTERING AND OTHER EFFECTS

Ya. B. ZEL' DOVICH

Submitted to JETP editor December 25, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) **36**, 964–966 (March, 1959)

Brilliant Speculation

Is Electron Scattering Parity-Violating?

WE assume that besides the weak interaction that causes beta decay,

$$g\,(\bar{P}ON)(\bar{e}^{-}O\nu) + \text{Herm. conj.}, \qquad (1)$$

there exists an interaction

$$\boxed{g\,(\bar{P}OP)(\bar{e}^{-}Oe^{-})} \qquad (2)$$

with $g \approx 10^{-49}$ and the operator $O = \gamma_\mu (1 + i\gamma_5)$ characteristic[1] of processes in which parity is not conserved.*

Then in the scattering of electrons by protons the interaction (2) will interfere with the Coulomb scattering, and the nonconservation of parity will appear in terms of the first order in the small quantity g. Owing to this it becomes possible to test the hypothesis used here experimentally and to determine the sign of g.

In the scattering of fast ($\sim 10^9$ ev) longitudinally polarized electrons through large angles by unpolarized target nuclei it can be expected that the cross-sections for right-hand and left-hand electrons (i.e., for electrons with $\sigma \cdot p > 0$ and $\sigma \cdot p < 0$) can differ by 0.1 to 0.01 percent. Such an effect is a specific test for an interaction not conserving parity.

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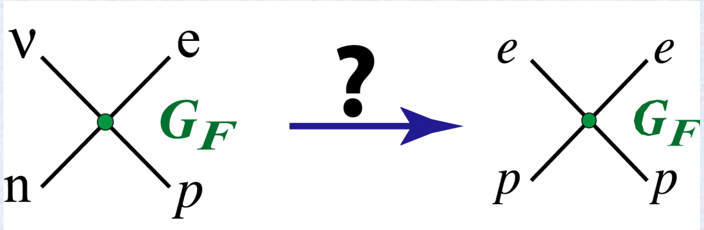
Electron-proton Weak Scattering



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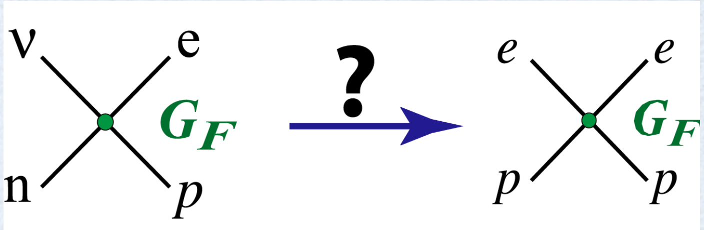

$$\sigma \;\; \alpha \; |A_{\mathrm{EM}} + A_{\mathrm{weak}}|^2$$

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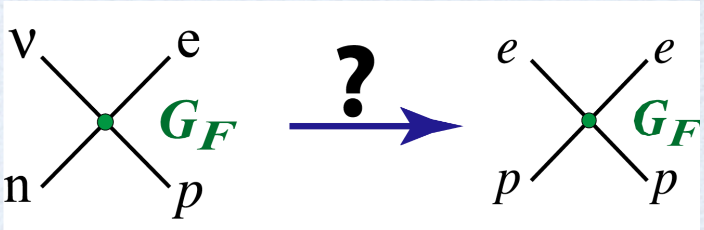

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Parity-violating

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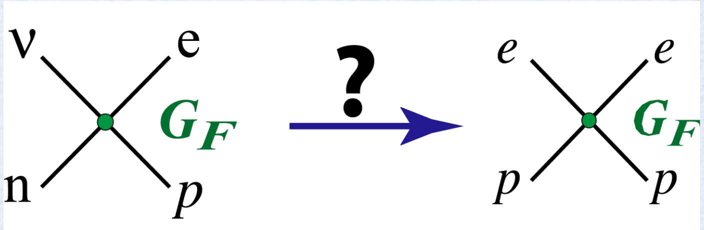

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$$A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} = -A_{LR}$$

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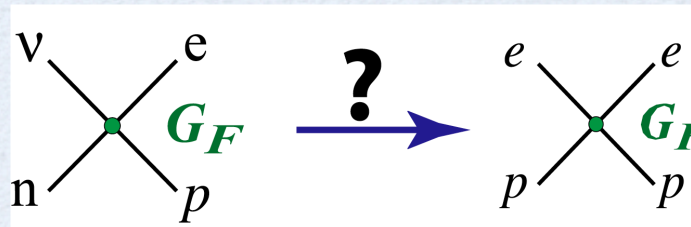

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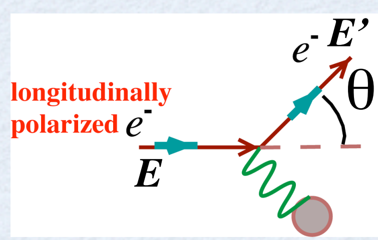
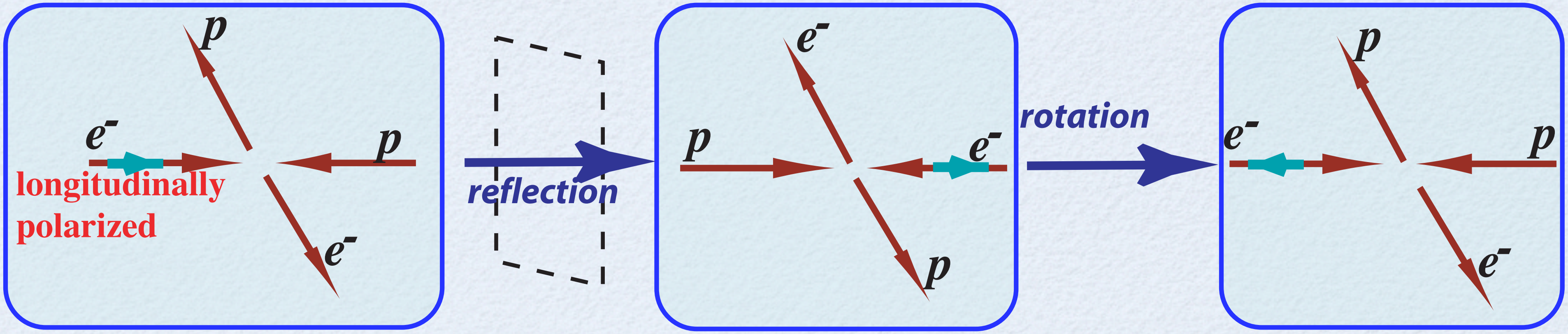


4-momentum transfer

$$Q^2 = 4EE'\sin^2\frac{\theta}{2}$$

Parity Violation Signature

How to observe parity-violation in electron scattering



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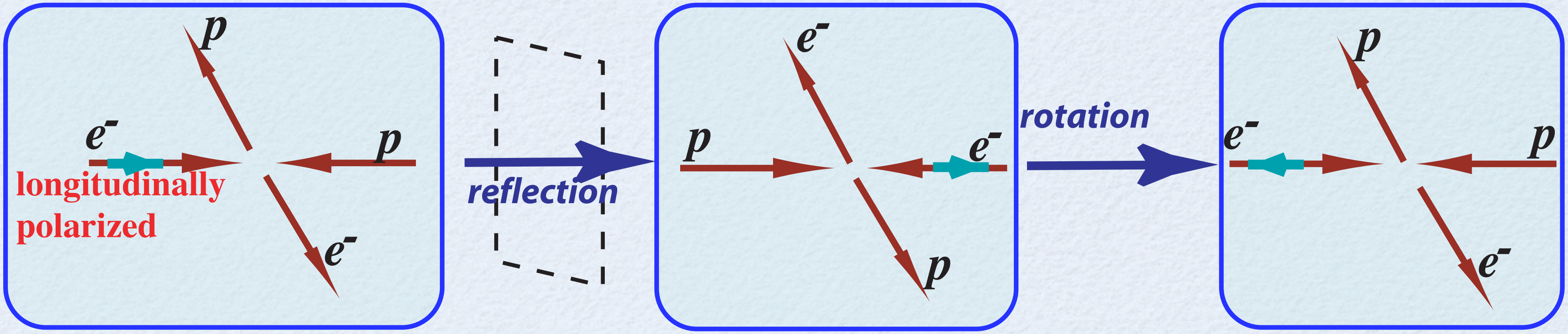

- *One of the incident beams longitudinally polarized*
- *Change sign of longitudinal polarization*
- *Measure fractional rate difference*

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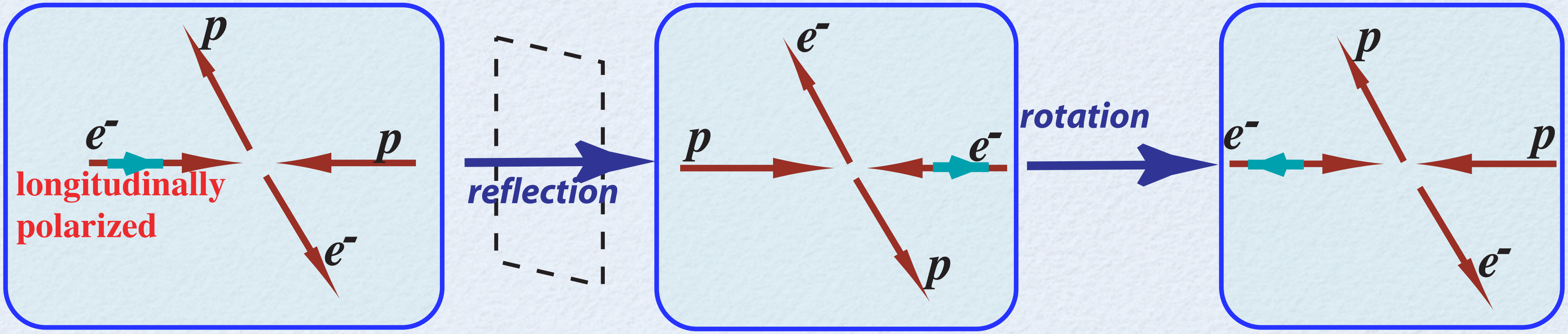

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The matrix element of the Coulomb scattering is of the order of magnitude e^2/k^2, where k is the momentum transferred ($\hbar = c = 1$). Consequently, the ratio of the interference term to the Coulomb term is of the order of gk^2/e^2. Substituting $g = 10^{-5}/M^2$, where M is the mass of the nucleon, we find that for $k \sim M$ the parity non-conservation effects can be of the order of 0.1 to 0.01 percent.

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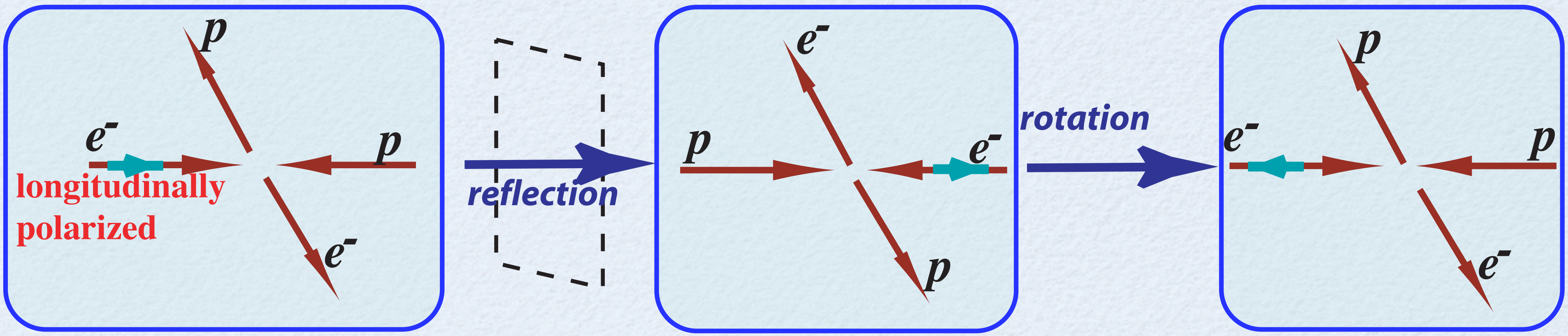

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$$A_{PV} = \frac{\sigma_{\uparrow} - \sigma_{\downarrow}}{\sigma_{\uparrow} + \sigma_{\downarrow}} \sim \frac{A_{weak}}{A_{EM}} \sim \frac{G_F Q^2}{4\pi\alpha}$$

$$A_{PV} \sim 10^{-4} \cdot Q^2(\mathrm{GeV}^2)$$

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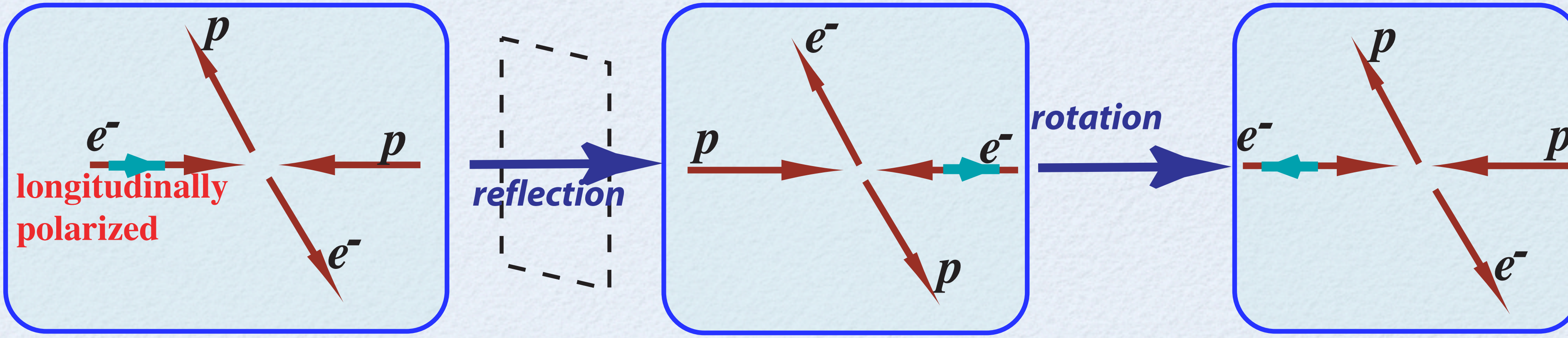

- *One of the incident beams longitudinally polarized*
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The idea could not be tested
for 2 decades:
Two different happenstances aligned
to bring about a landmark experiment

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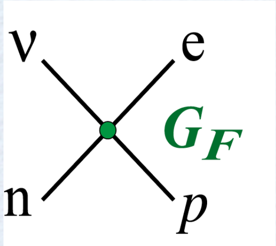
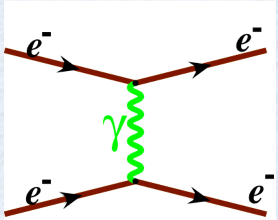
Electroweak Unification?

Similar to the landmark unification of electric and magnetic forces via Maxwell's Equations



Early 1950s: attempts to describe weak and electromagnetic interactions in a unified framework



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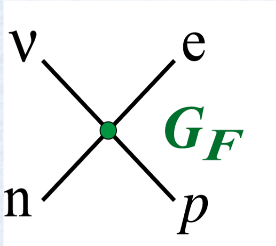

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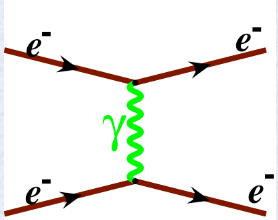

Weak interactions are short range

massive force carriers are W bosons ~ 80 GeV

$$V = \frac{1}{4\pi\varepsilon_0}\frac{q}{r}\, e^{[-0.45\ (\text{attometer})^{-1} \times r]}$$

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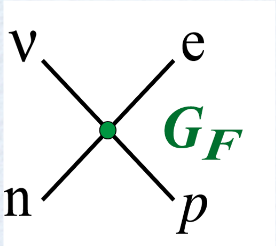

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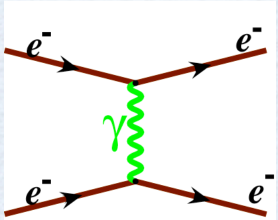

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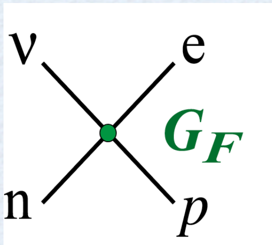

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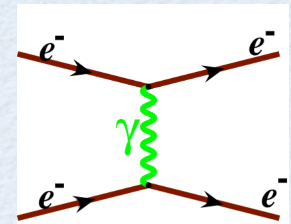

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Weak interactions are parity-violating

(V-A)

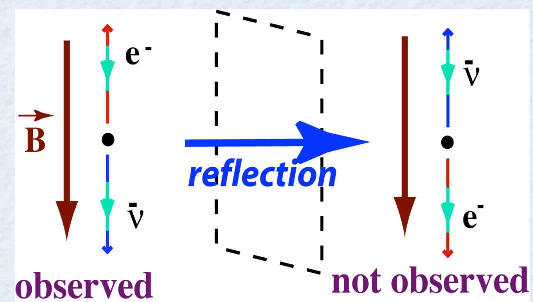
matter particles have spin = 1/2

$$h = \frac{\vec{s} \bullet \vec{p}}{|\vec{s}||\vec{p}|} = \pm 1$$

handedness or ***helicity/chirality***

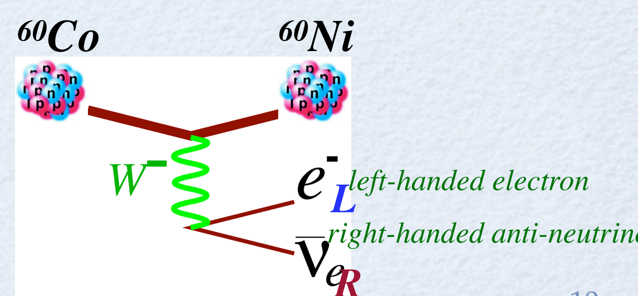
Mirror reflection flips sign of helicity

Left-handed ⟺ ***right-handed***



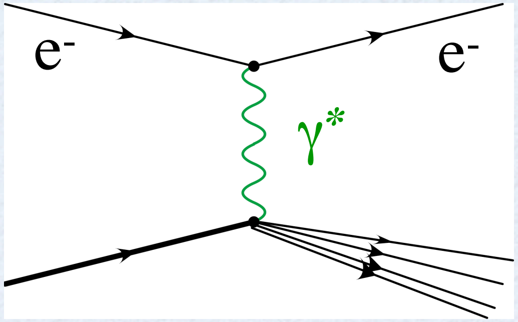
Only left-handed particles can exchange W bosons

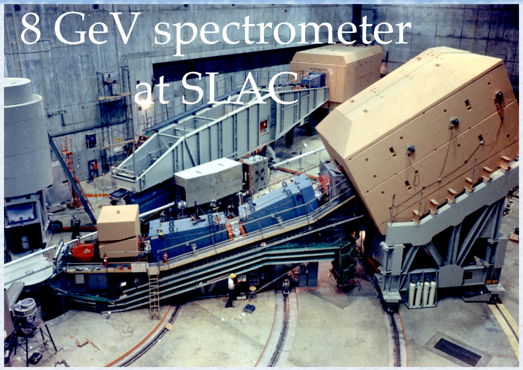
(right-handed anti-particles)



Deep Inelastic Scattering

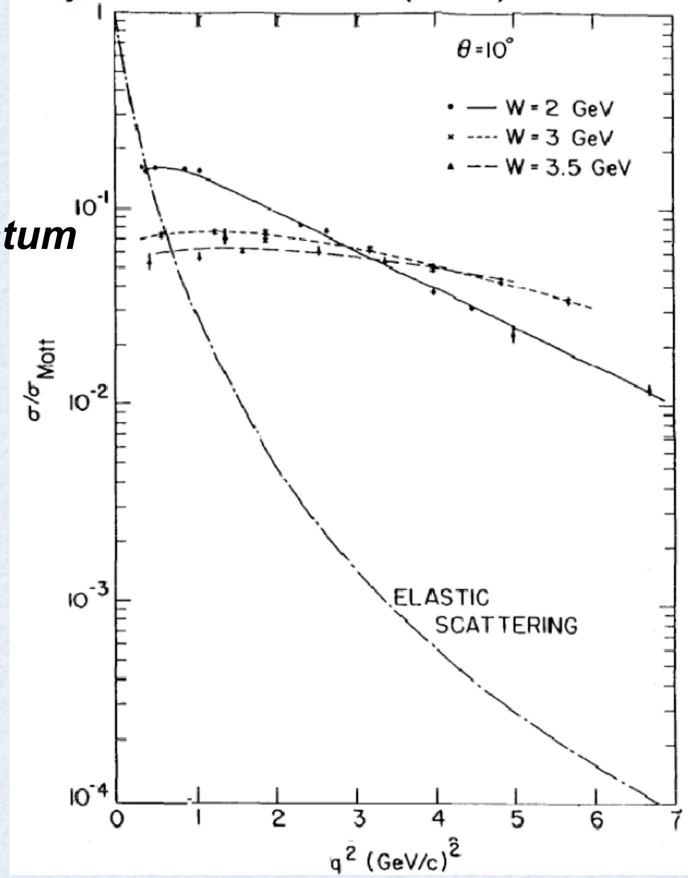
...and the birth of polarized electron beams





W = Mass of recoiling fragments

M. Briedenbach et al,
Phys Rev Lett 23, 935 (1969)



need to measure both scattering angle and scattered momentum

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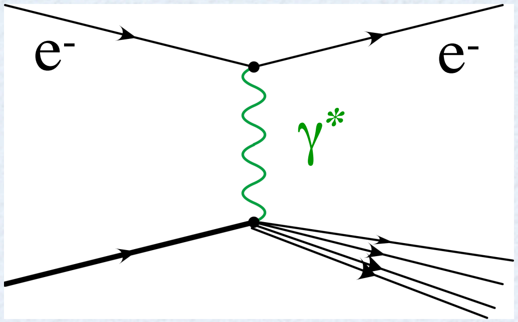

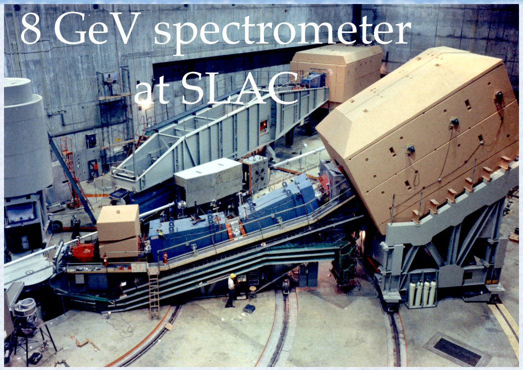

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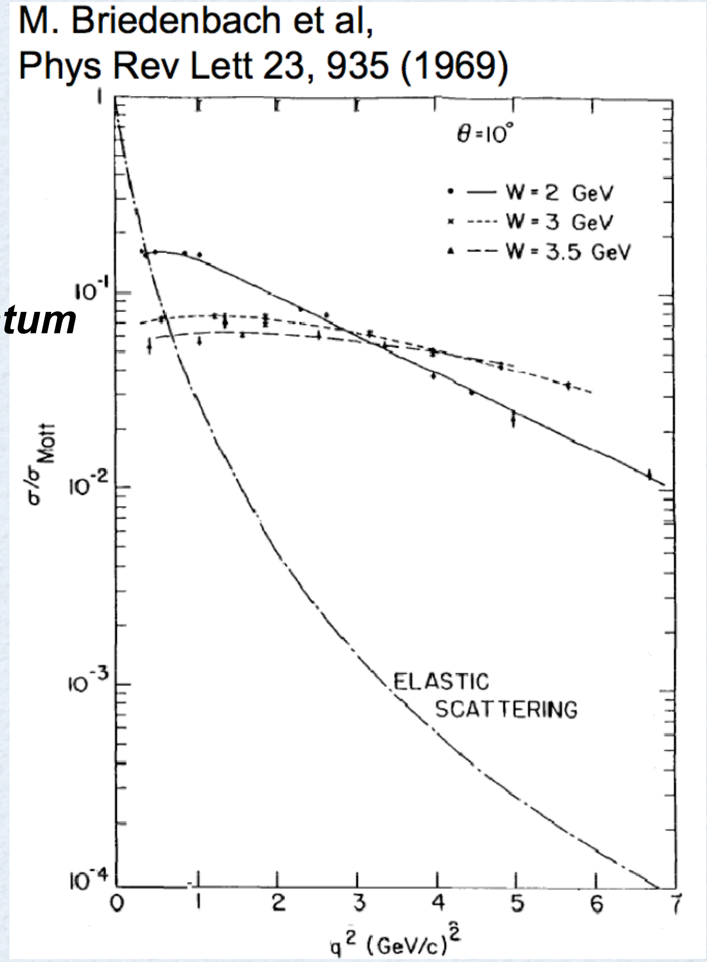

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electrons are hitting structureless objects that have negligible size!

Happenstance #1

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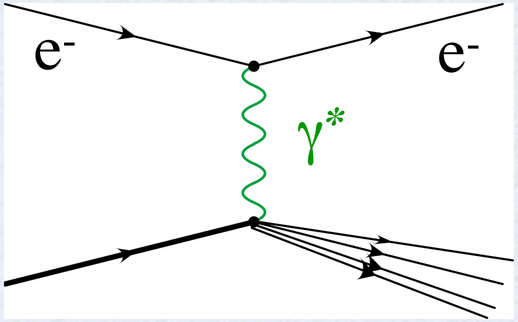

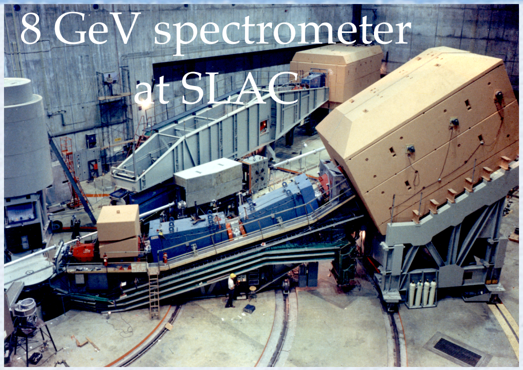

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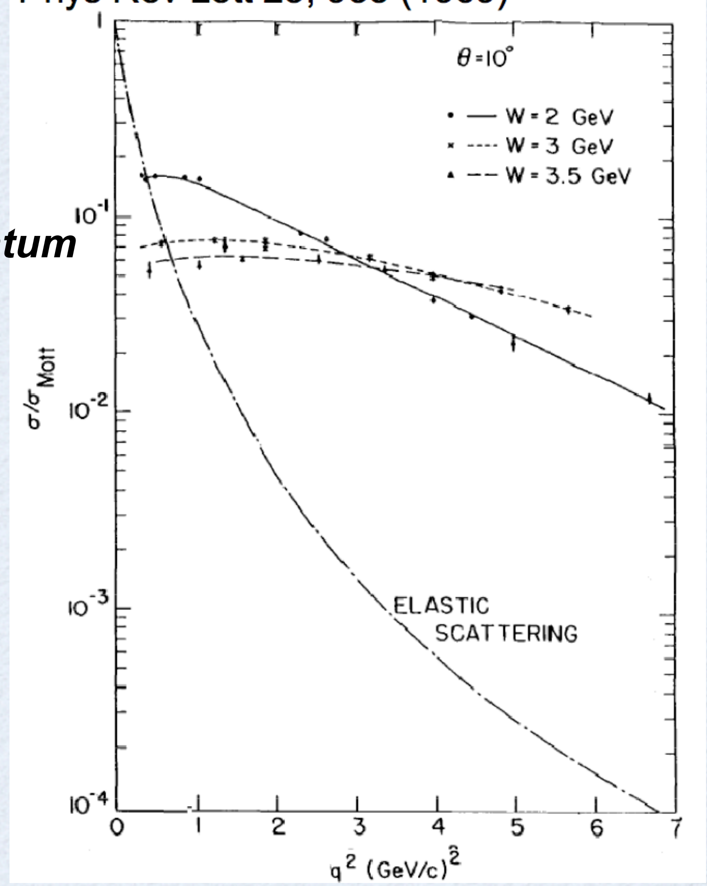

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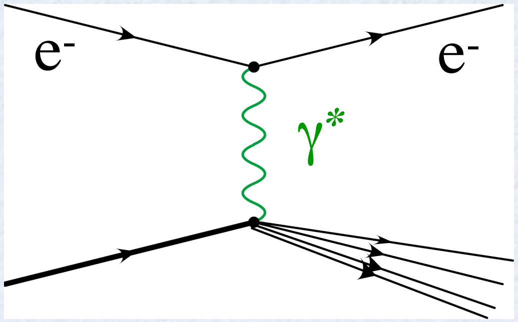

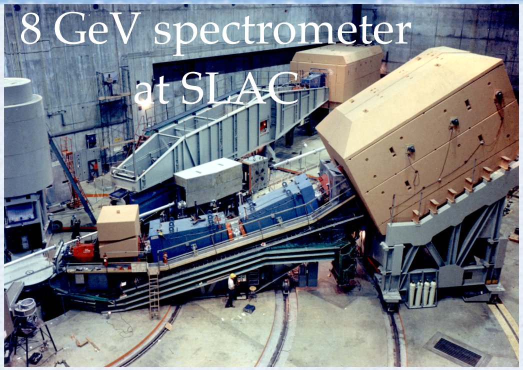

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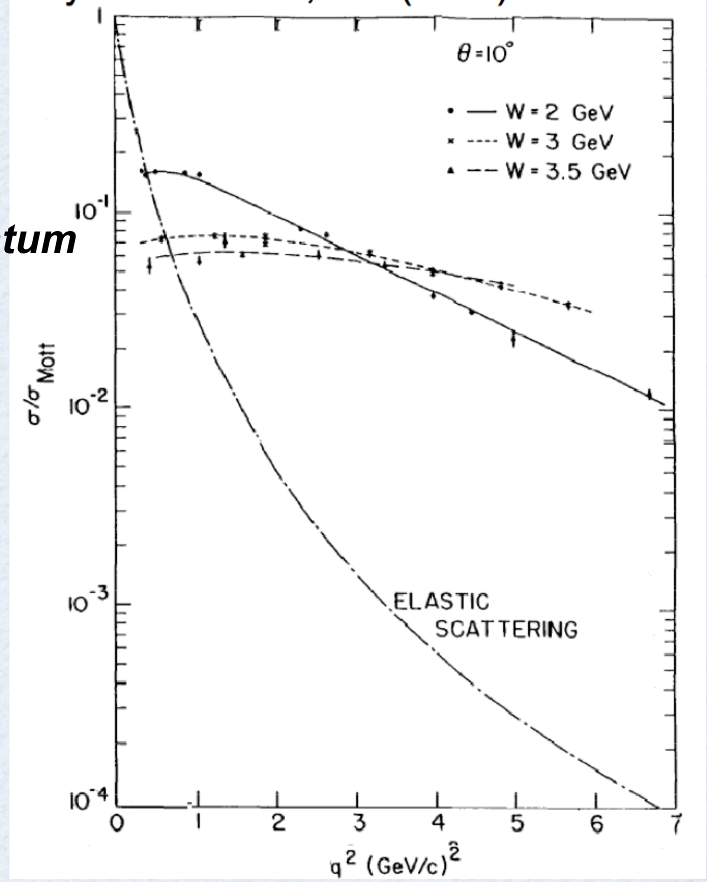

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High scattering rates possible at high Q^2!

In order to probe the quark structure of hadrons:

motivation for the development of polarized electron beams

Birth of high energy spin physics

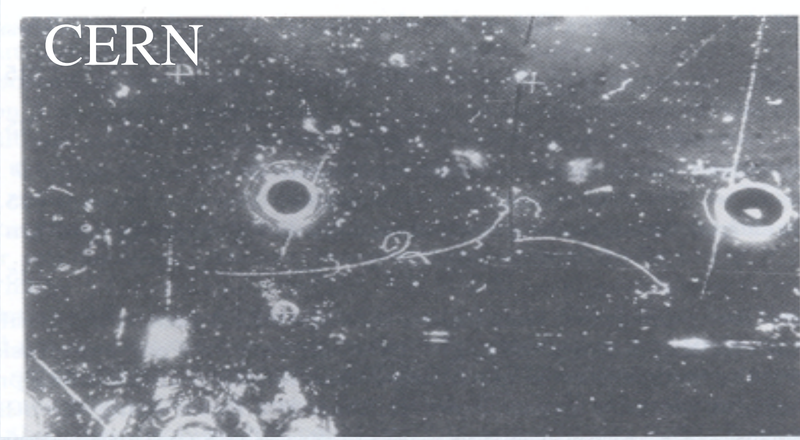
Happenstance #2

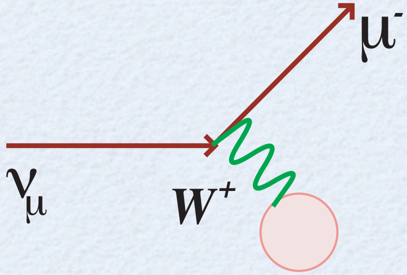
Neutral Weak Interaction Theory

A Model of Leptons: Steven Weinberg (1967)

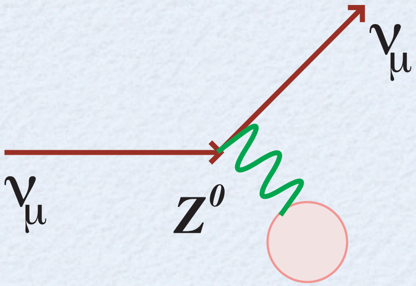
The Z boson incorporated

Gargamelle finds one ν_μ e^- event in 1973!
(two more by 1976)





Charged Current



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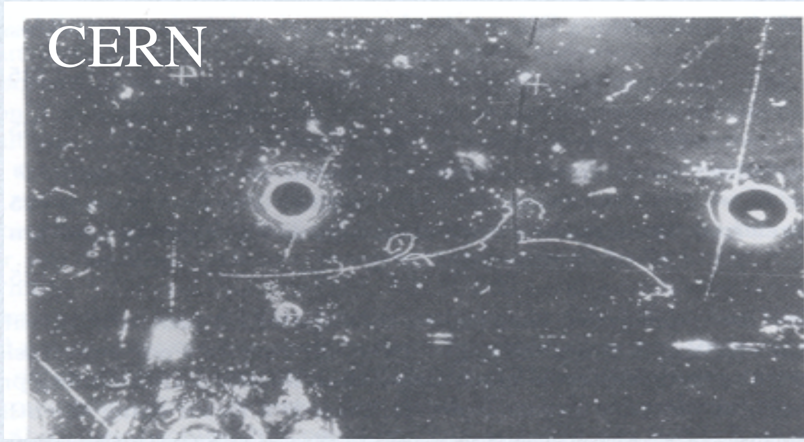

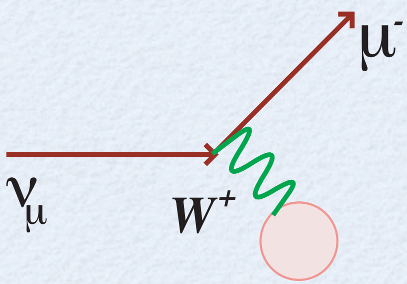

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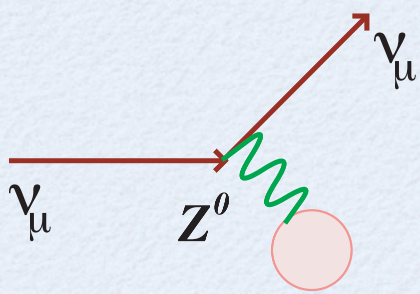

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	Left- g_L	**Right-** g_R
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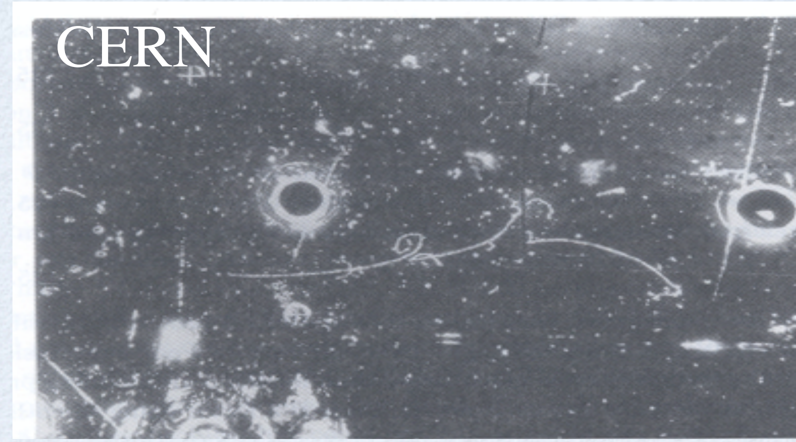

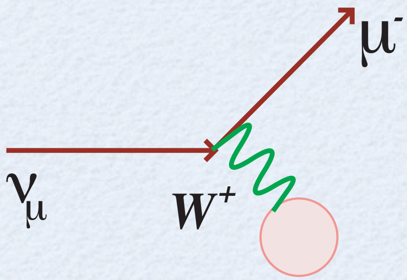

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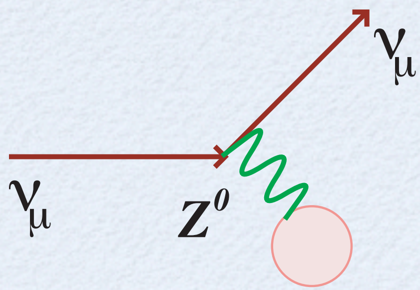

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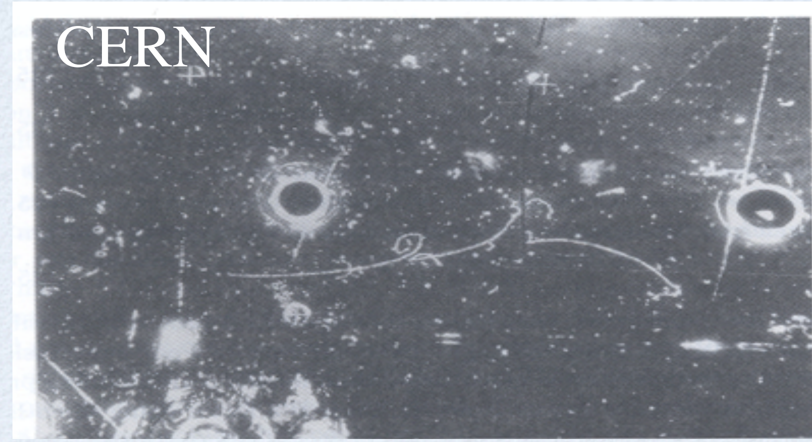

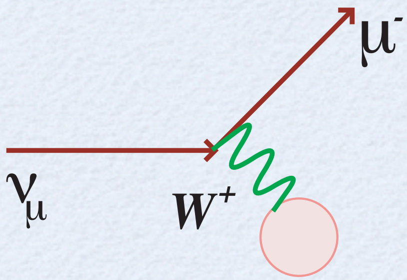

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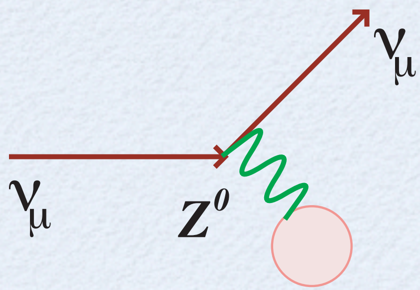

Neutral Current

One free parameter: the weak mixing angle θ_W introduced

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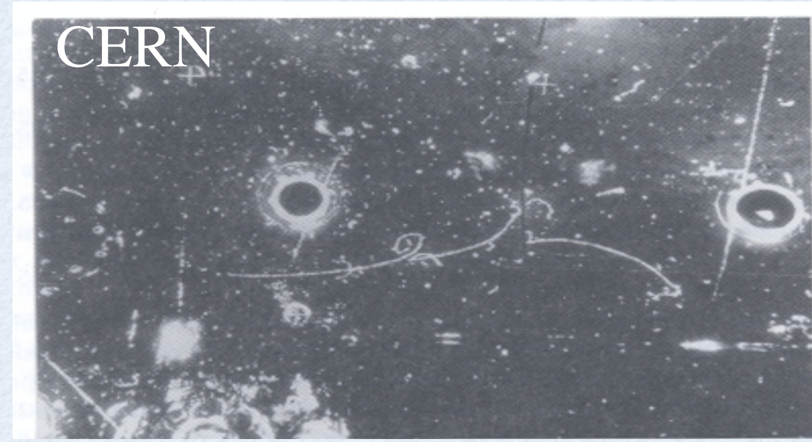

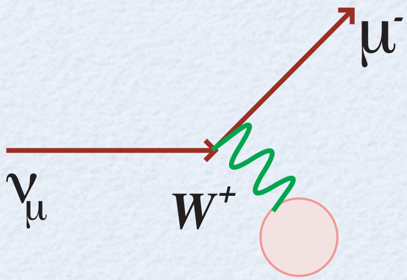

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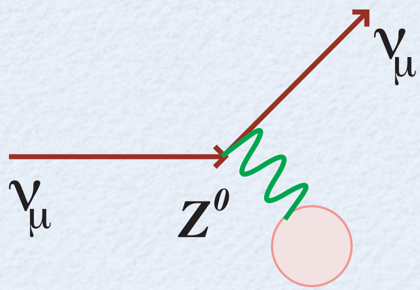

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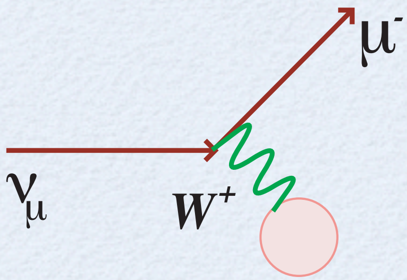

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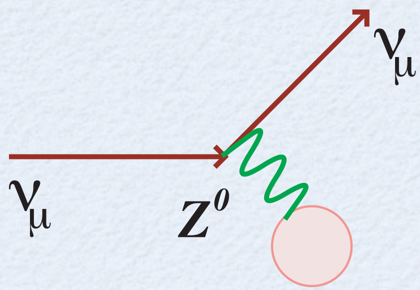

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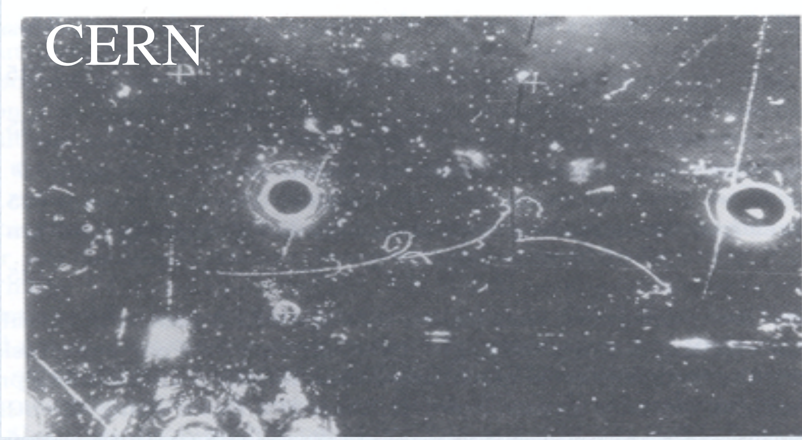

One free parameter: the weak mixing angle θ_W introduced

If θ_W were strictly zero, W & Z bosons would weigh exactly the same and right-handed charged particles would not exchange Z bosons either

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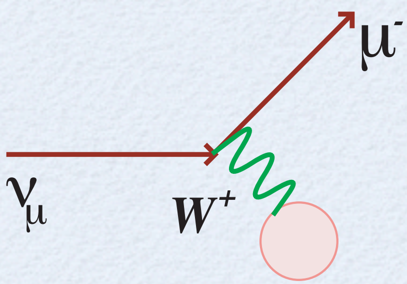

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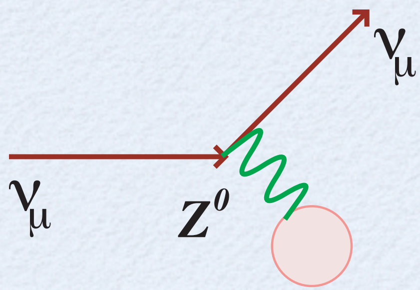

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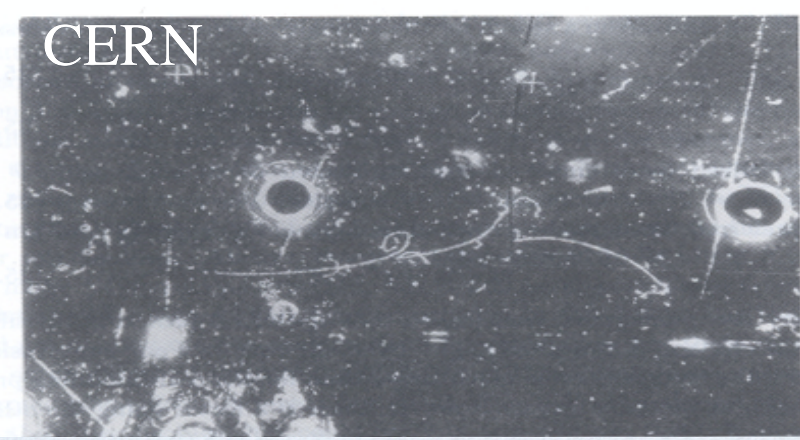

Neutrino scattering measurements find θ_W is non-zero

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A Pressing Question

Is Electron Scattering Parity-Violating?

consider electron-nucleon deep inelastic scattering

$$\begin{pmatrix}\nu \\ e\end{pmatrix}_l \quad (e)_r$$

Weinberg model

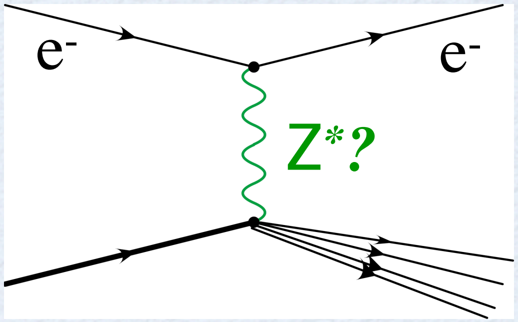
Parity is violated

$$A_{PV} \sim 10^{-4}$$

or

$$\begin{pmatrix}\nu \\ e\end{pmatrix}_l \quad \begin{pmatrix}E^\circ \\ e\end{pmatrix}_r$$

Parity is conserved



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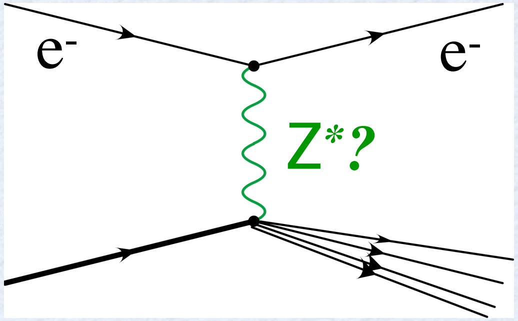
$$A_{PV} \sim 10^{-4}$$

or

$$\begin{pmatrix} \nu \\ e \end{pmatrix}_l \quad \begin{pmatrix} E^0 \\ e \end{pmatrix}_r$$

Parity is conserved



First Generation Source: ***Intensity too low to obtain statistics***

Slow reversal of spin ~ 1 min

mid-1970's

A Pressing Question

Is Electron Scattering Parity-Violating?

consider electron–nucleon deep inelastic scattering

$$\begin{pmatrix}\nu\\ e\end{pmatrix}_l \quad (e)_r$$

or

$$\begin{pmatrix}\nu\\ e\end{pmatrix}_l \quad \begin{pmatrix}E^\circ\\ e\end{pmatrix}_r$$

Weinberg model

Parity is violated

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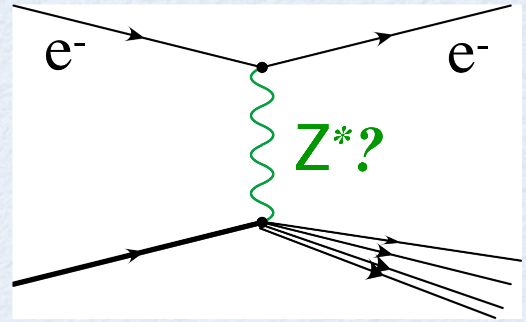

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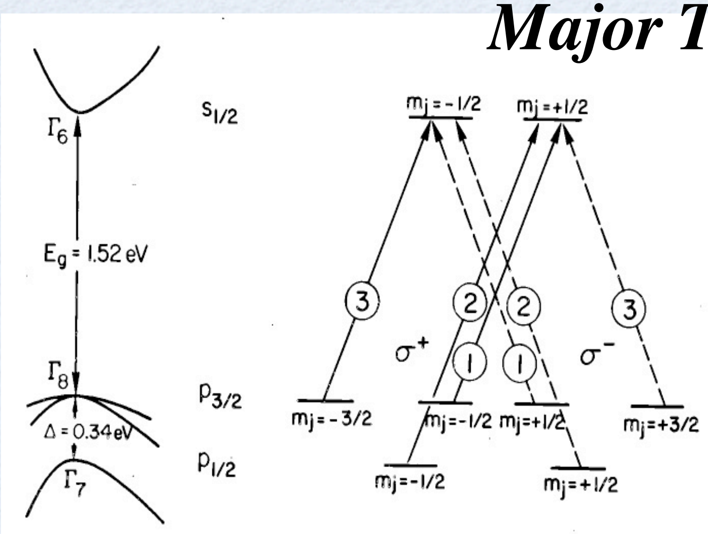
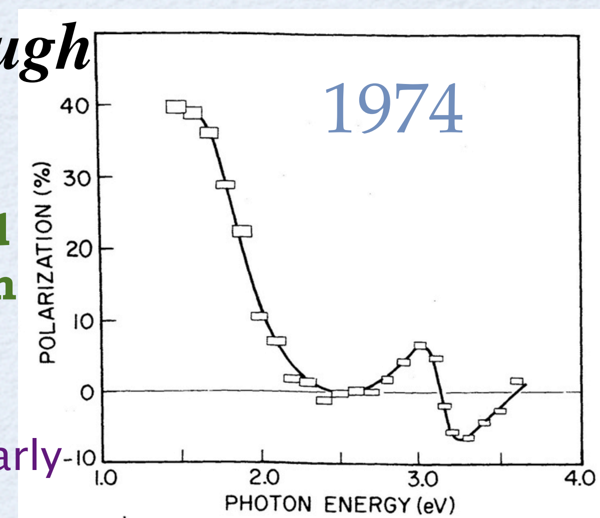
Major Technical Breakthrough

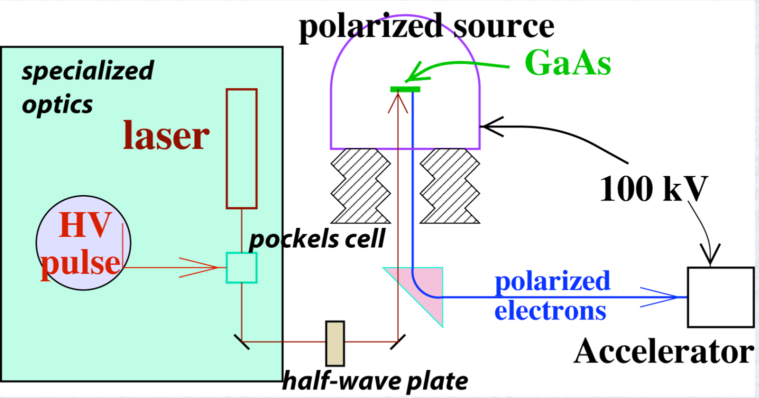


GaAs photocathode:
longitudinally polarized electron beam with high intensity and stability

optical pumping with circularly polarized laser light



Anatomy of a Parity Experiment



·**Optical pumping of a GaAs wafer: "black magic" chemical treatment to boost quantum efficiency**

·**Rapid helicity reversal: polarization sign flips ~ 100 Hz to minimize the impact of drifts**

·**Helicity-correlated beam motion: under sign flip, beam stability at the micron level**

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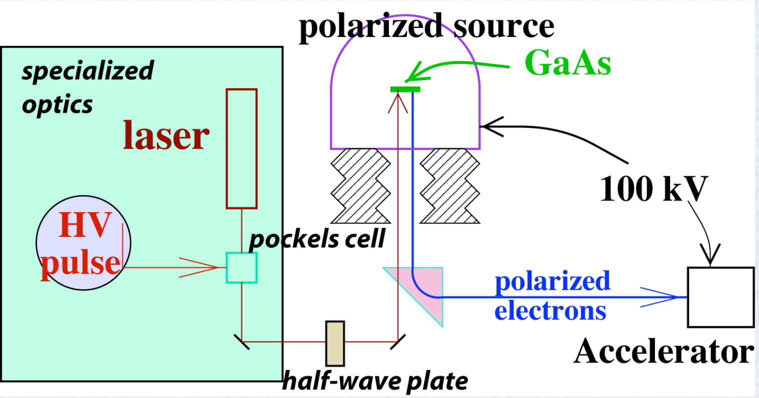

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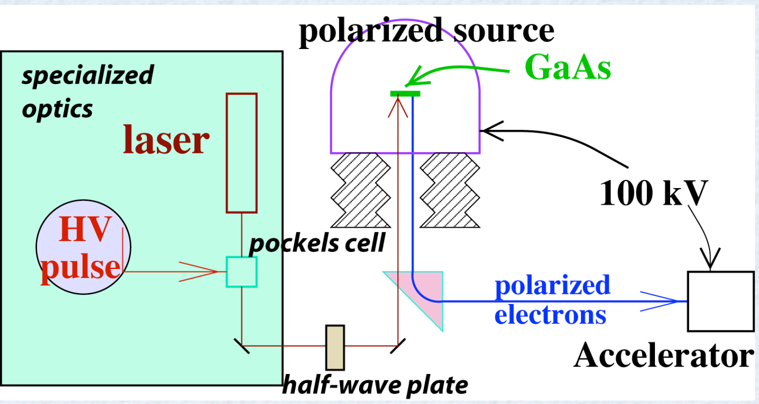

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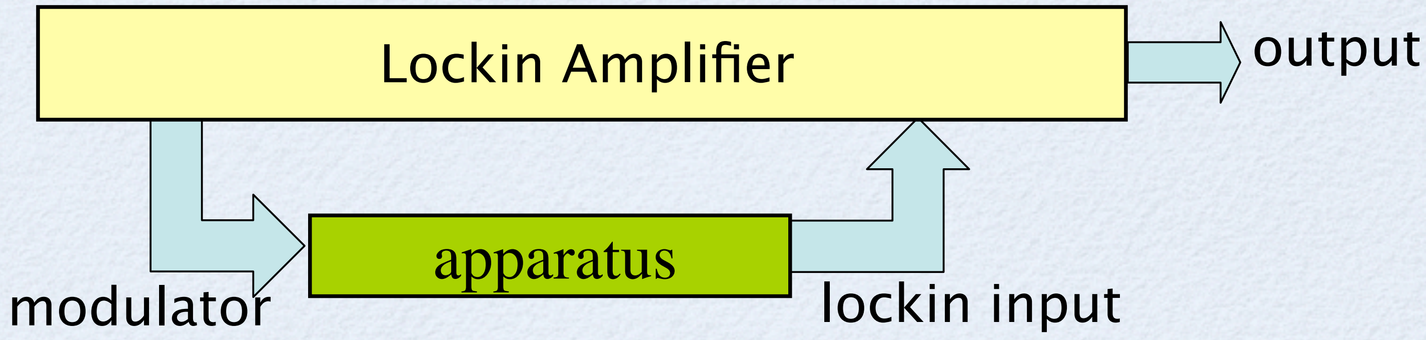
Tiny signal buried in known background



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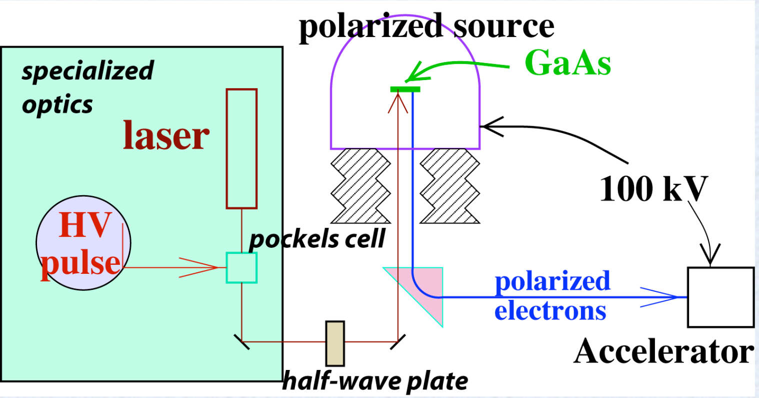

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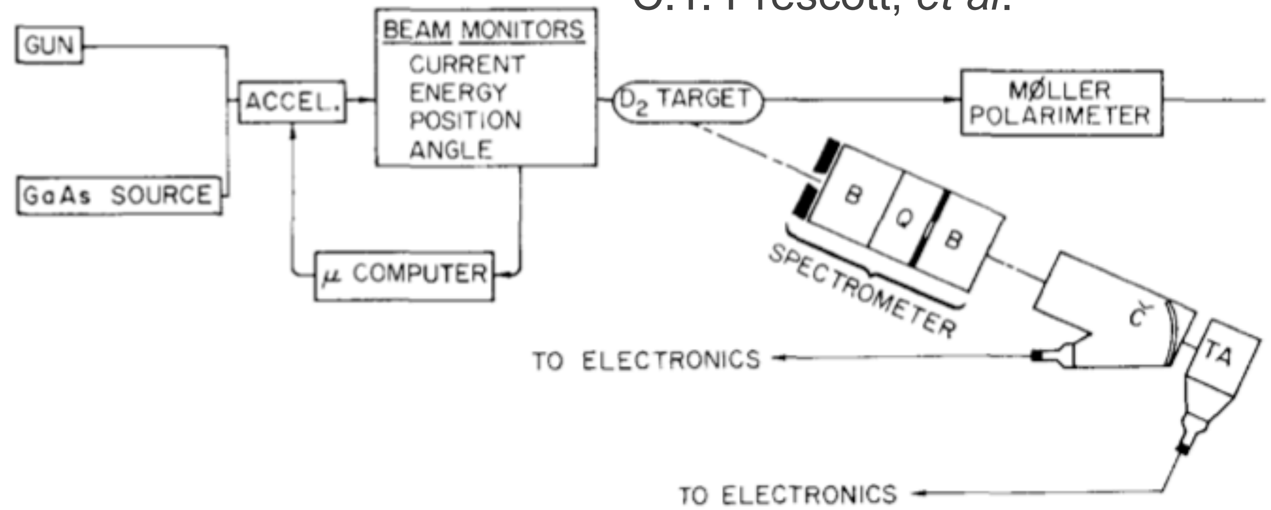
Lockin Amplifier ⇨ output

injector ⇨ ***accelerator*** ⇨ ***target*** ⇨ ***spectrometer*** ⇨ ***detector***

Anatomy of a Parity Experiment

C.Y. Prescott, *et al.*



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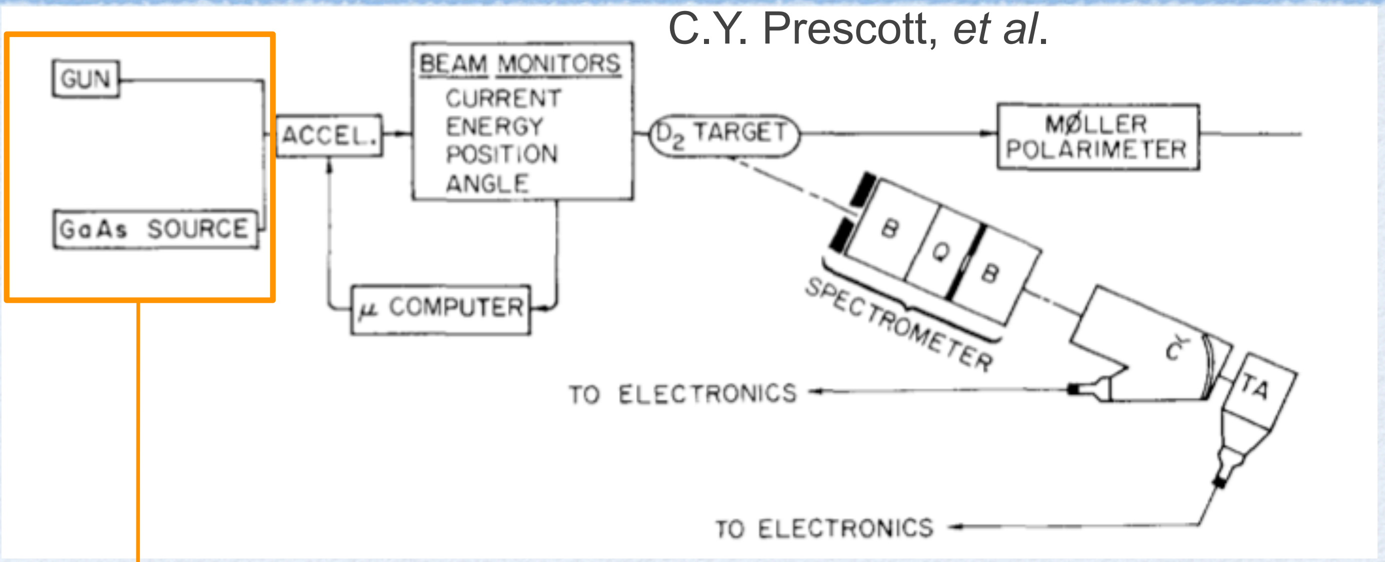
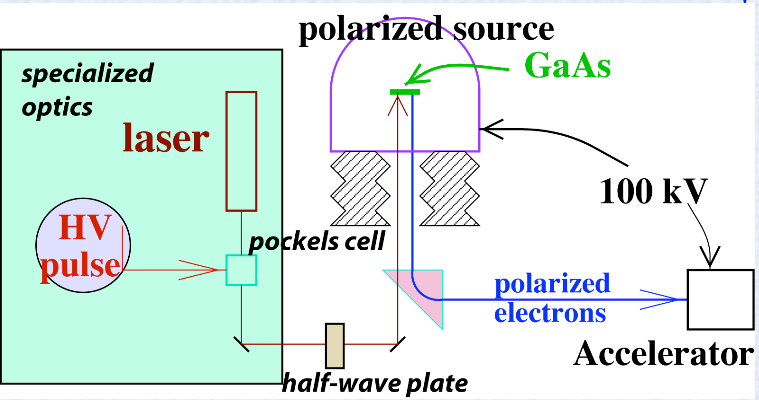
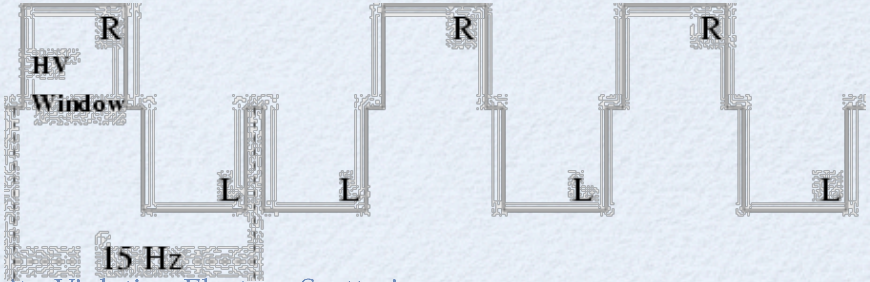
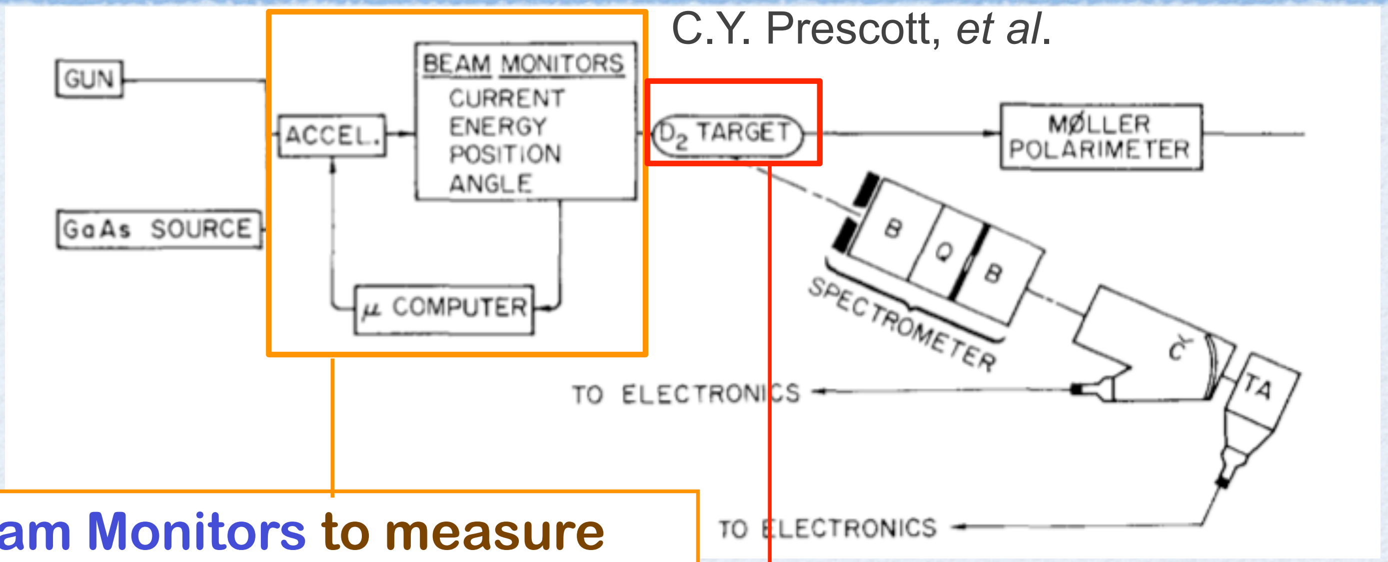




- ✧ **Beam helicity sequence is chosen pseudo-randomly**
  - Helicity state, followed by its complement
  - Data analyzed as "pulse-pairs"



Anatomy of a Parity Experiment

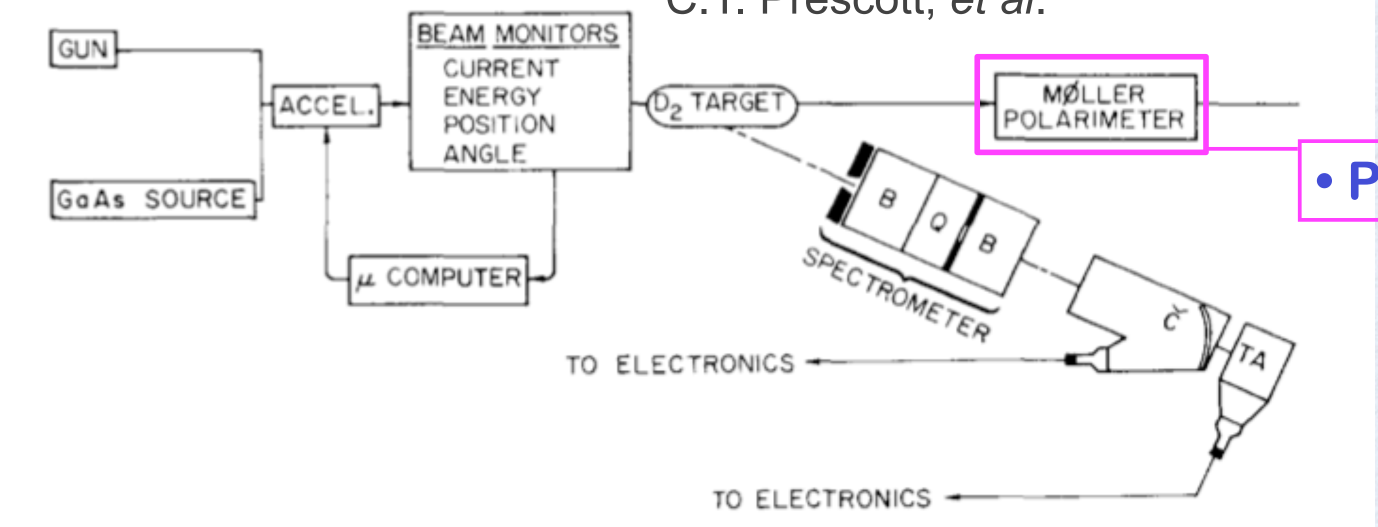


- **Beam Monitors to measure helicity-correlated changes in beam parameters**

- **High-power cryotarget 30 cm long for high luminosity**

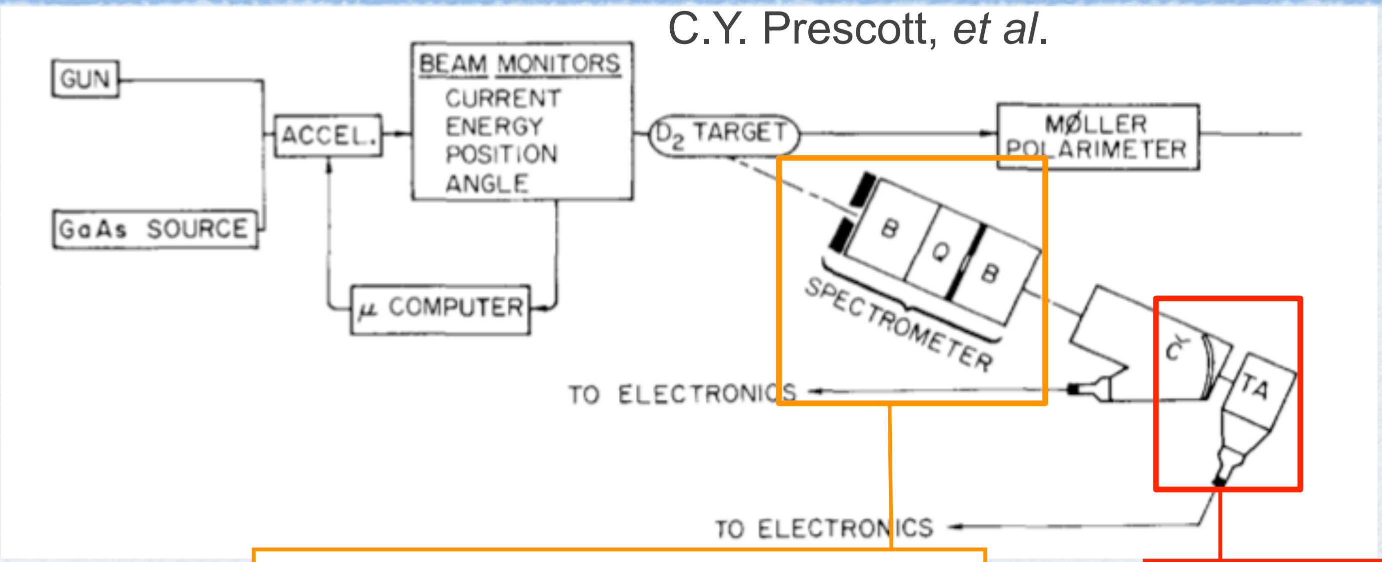
Anatomy of a Parity Experiment

C.Y. Prescott, *et al.*



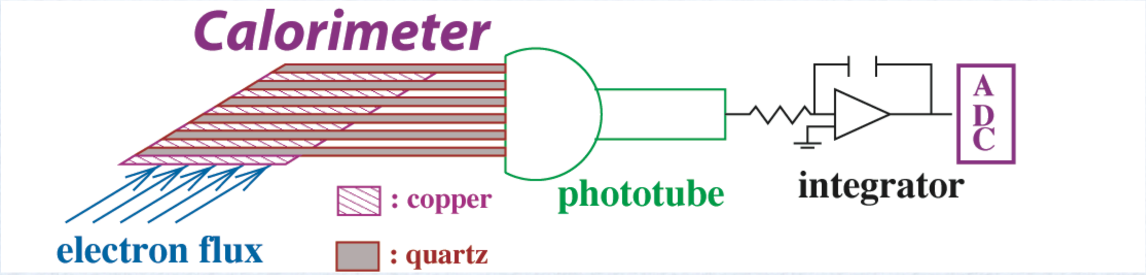
- **Polarimetry**

Anatomy of a Parity Experiment



- **Magnetic spectrometer** directs flux to background-free region

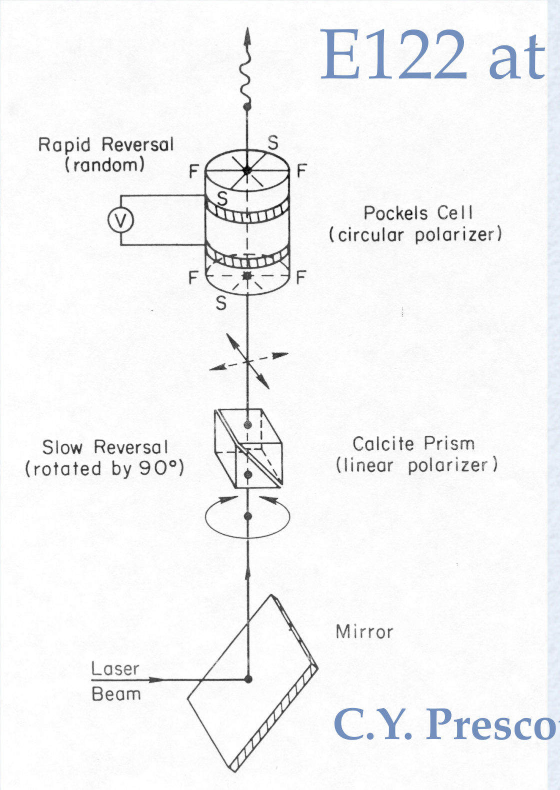
- **Flux Integration** measures high rate without deadtime

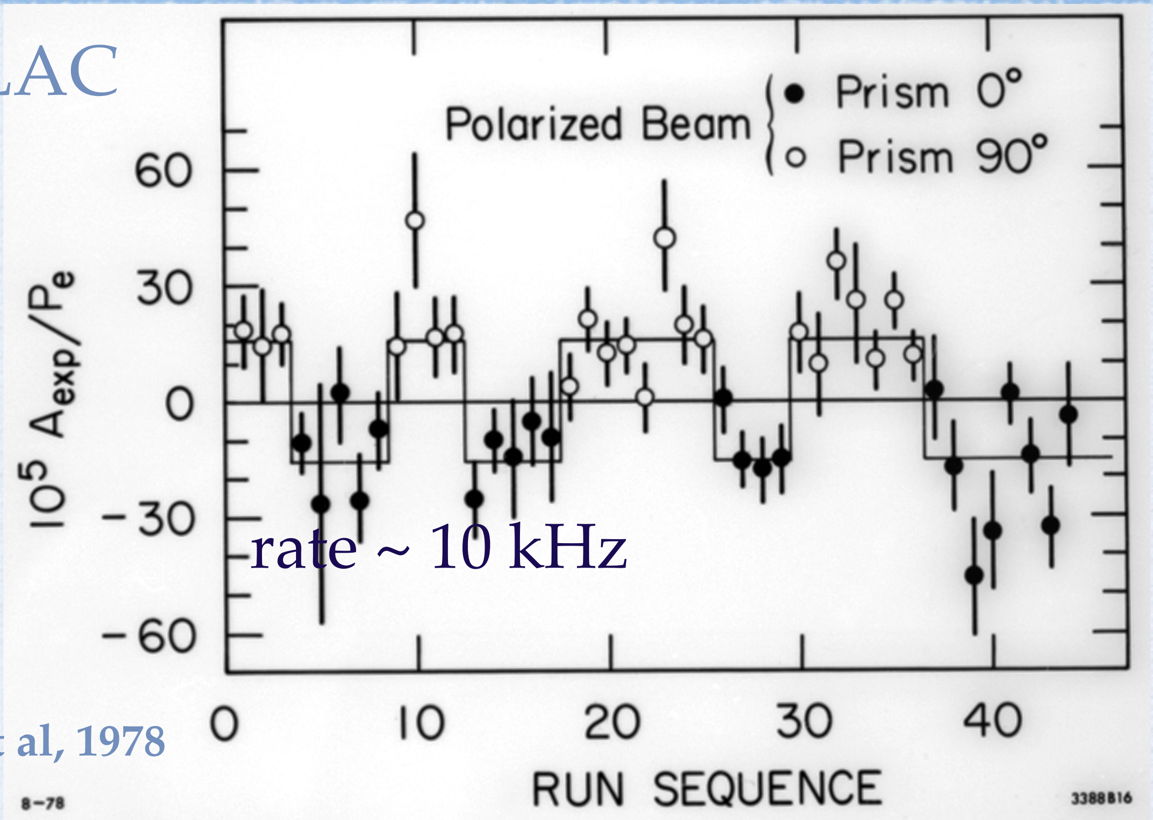


A Landmark Result

Does the weak neutral current amplitude interfere with the electromagnetic amplitude?

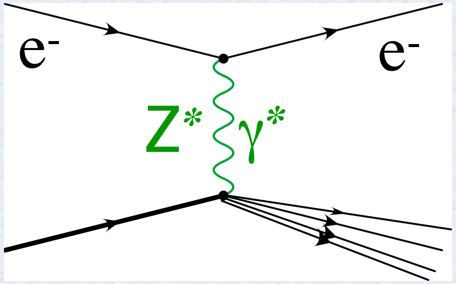
E122 at SLAC





rate ~ 10 kHz

C.Y. Prescott et al, 1978



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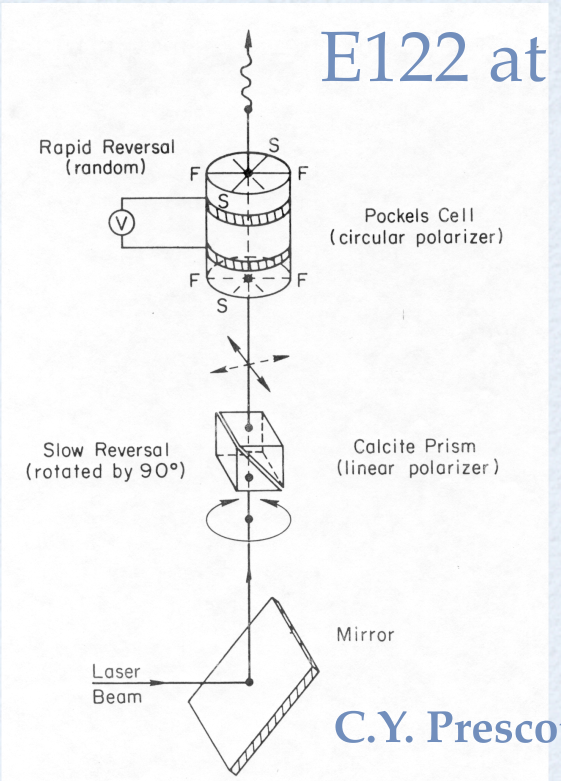

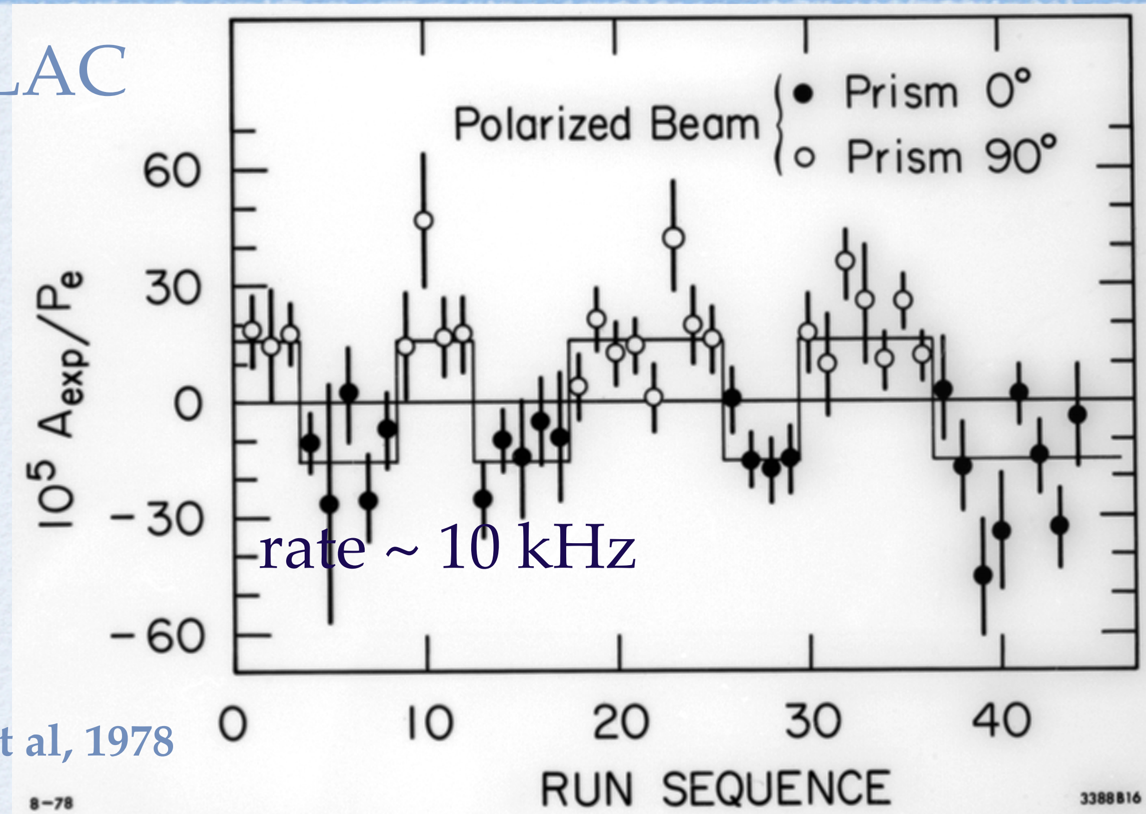

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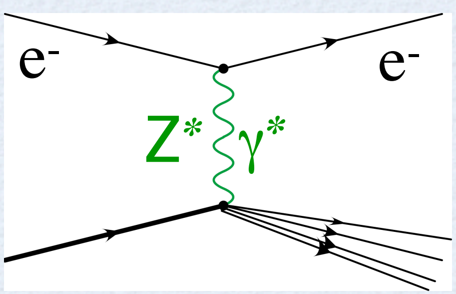

- ***Parity Violation in Weak Neutral Current Interactions***
- ***$\sin^2\theta_W$ = 0.224 ± 0.020: same as in neutrino scattering***

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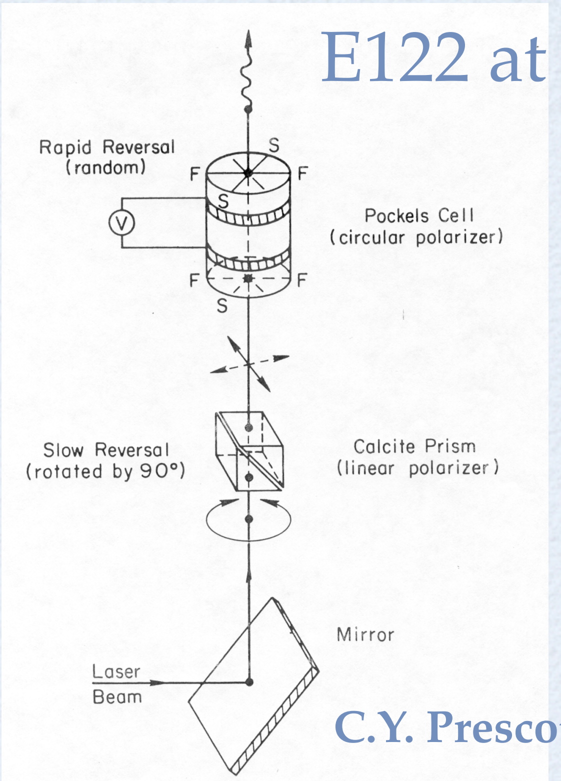

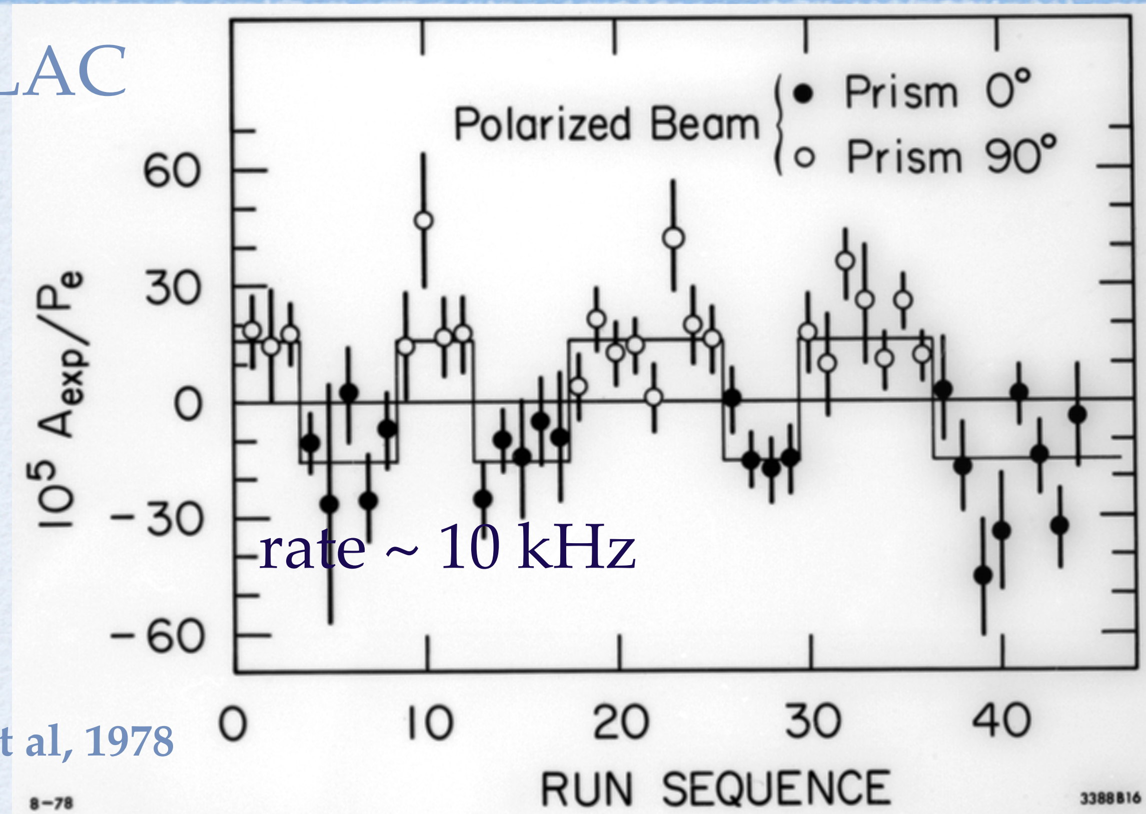

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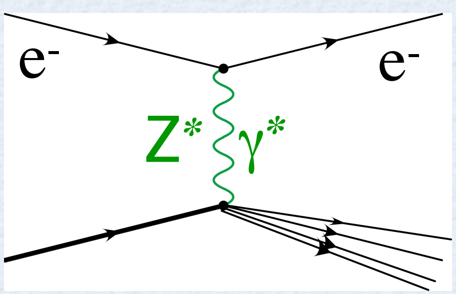

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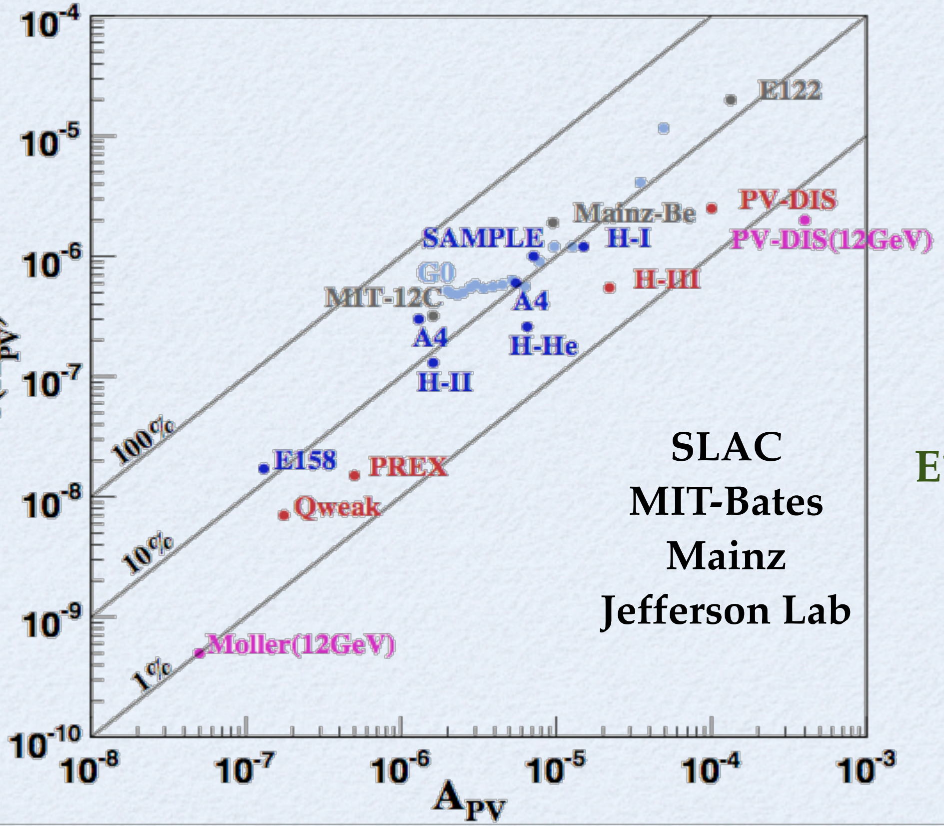
Glashow, Weinberg, Salam Nobel Prize awarded in 1979

3 Decades of Technical Progress

Continuous interplay between probing hadron structure and electroweak physics

Parity-violating electron scattering has become a precision tool



- *Beyond Standard Model Searches*
- *Strange quark form factors*
- *Neutron skin of a heavy nucleus*
- *QCD structure of the nucleon*

Mainz & MIT-Bates in the mid-80s

JLab program launched in the mid-90s

E158 at SLAC measured PV Møller scattering

State-of-the-art:

- ***sub-part per billion statistical reach and systematic control***
- ***sub-1% normalization control***

- ***photocathodes, polarimetry, high power cryotargets, nanometer beam stability, precision beam diagnostics, low noise electronics, radiation hard detectors***

50's & 60's: Electron Scattering probed nuclear and nucleon substructure

70's: Parity-violating deep inelastic scattering validated the electroweak theory

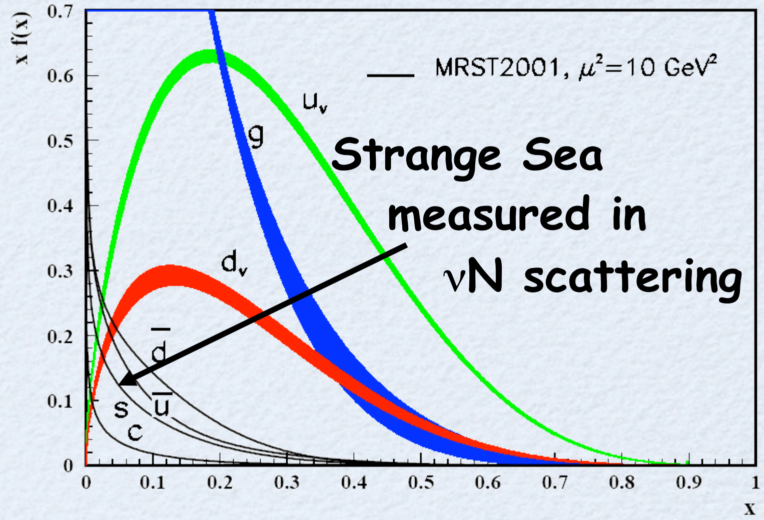
Parity-Violating Elastic Electron Scattering: Hadron Substructure

90's onwards: Physics ≤ 1 GeV

Strangeness in Nucleons

Quark Model ⟺ ? ⟺ QCD ***1980's***

Strange quarks carry nucleon momentum: Other external properties affected?



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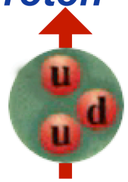
spin dependent deep inelastic scattering

$$S = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \Delta L$$

Proton Spin

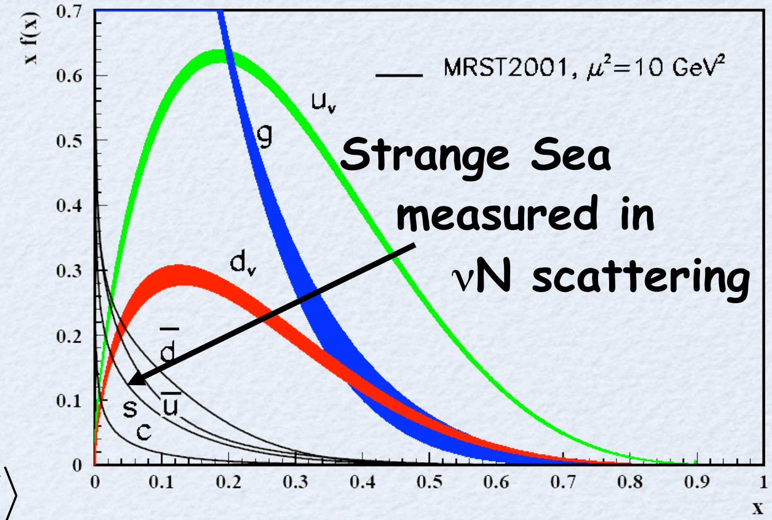


$$A_{\parallel} = \frac{\sigma_{\uparrow\uparrow} - \sigma_{\uparrow\downarrow}}{\sigma_{\uparrow\uparrow} + \sigma_{\uparrow\downarrow}}$$

Experiments:
$\Delta\Sigma \sim 0.25$

+ Hyperon decay
+ $SU(3)_f$ Symmetry:

$\Delta s \sim -0.1$?



Breaking of SU(3) flavor symmetry introduces uncertainties

$$\Delta s \sim \langle N | \bar{s}\gamma_\mu\gamma_5 s | N \rangle$$

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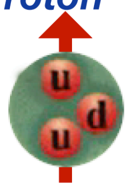

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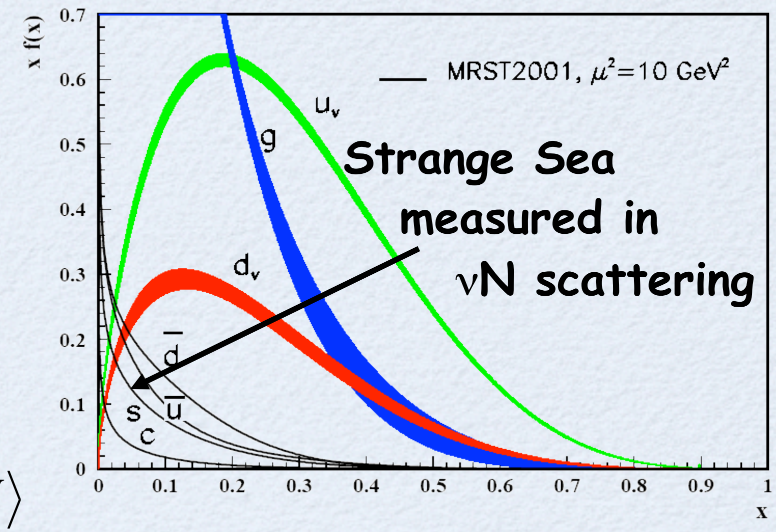
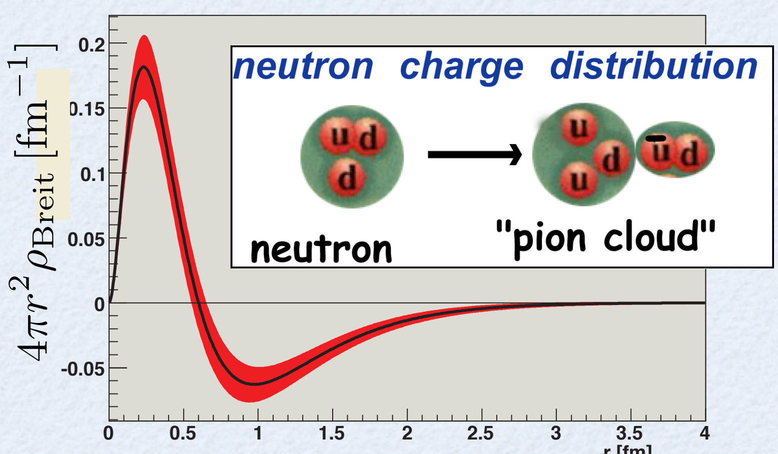
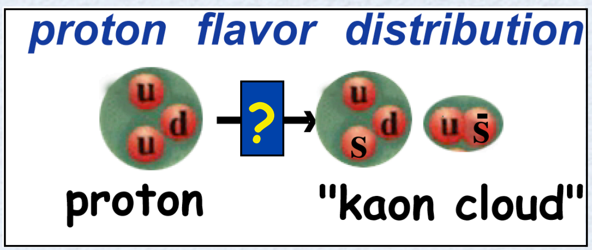


Breaking of SU(3) flavor symmetry introduces uncertainties

$$\Delta s \sim \langle N | \bar{s}\gamma_\mu\gamma_5 s | N \rangle$$

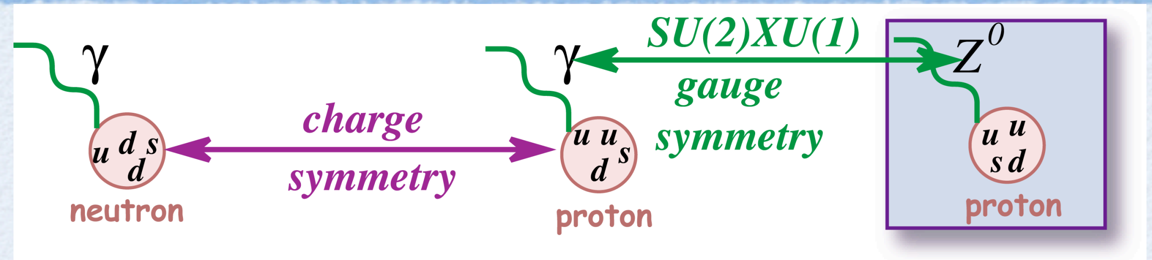
$$\langle N | \bar{s}\gamma_\mu s | N \rangle \neq 0\,?$$





Early calculations predicted substantial effects

Elastic Electroweak Scattering

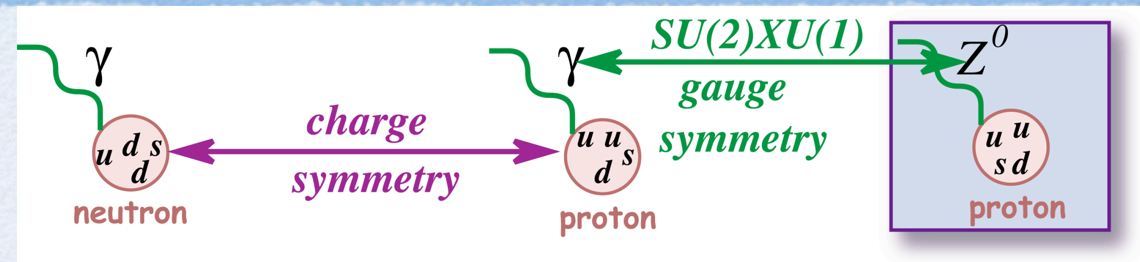


$$G_p^Z \sim (1 - 4\sin^2\theta_W)\, G_p^\gamma - G_n^\gamma - G_s$$

Kaplan & Manohar (1988)
McKeown (1990)

$G_E^s(Q^2), G_M^s(Q^2)$

Elastic Electroweak Scattering



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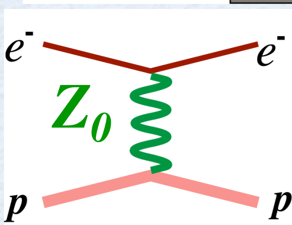

A_{PV} for elastic e-p scattering:

$$A = \left[\frac{-G_F Q^2}{4\pi\alpha\sqrt{2}}\right]\frac{A_E + A_M + A_A}{\sigma_p}$$

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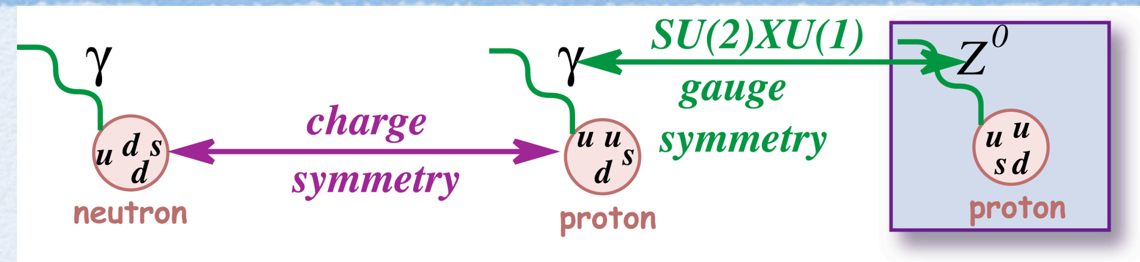

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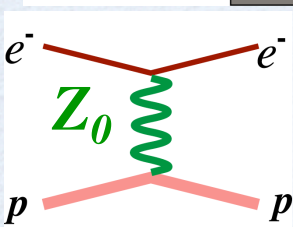

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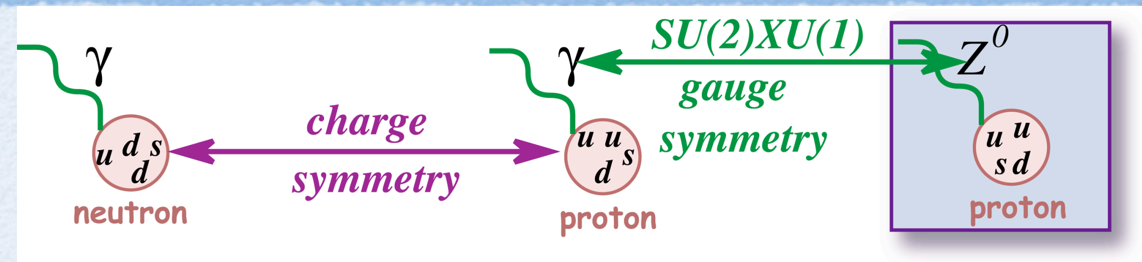
$$A_E = \epsilon\, G_E^p G_E^Z \qquad A_M = \tau\, G_M^p G_M^Z \qquad A_A = (1 - 4\sin^2\theta_W)\epsilon'\, G_M^p \tilde{G}_A$$

Forward angle Backward angle

"Anapole" radiative corrections are problematic

$$\mathbf{G^Z_{E,M} = (1 - 4\sin^2\theta_W) G^p_{E,M} - G^n_{E,M} - G^s_{E,M}}$$

Elastic Electroweak Scattering



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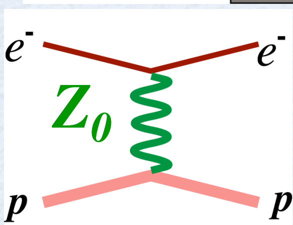

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Forward angle　　Backward angle

"Anapole" radiative corrections are problematic

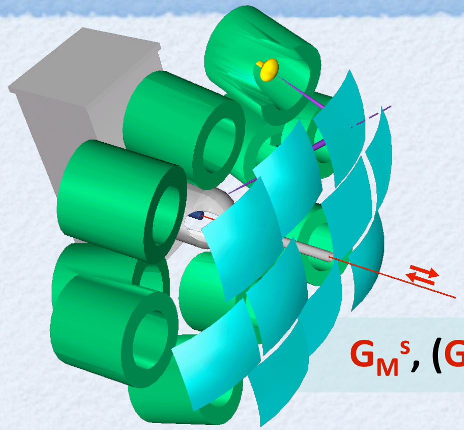
$$\mathrm{G_{E,M}^Z} = (1 - 4\sin^2\theta_W)\mathrm{G_{E,M}^p} - \mathrm{G_{E,M}^n} - \mathrm{G_{E,M}^s}$$

For a spin=0,T=0 ^{4}He: G^s_E **only!**

For deuterium: **Enhanced G_A**

World Program

1990-2010



SAMPLE

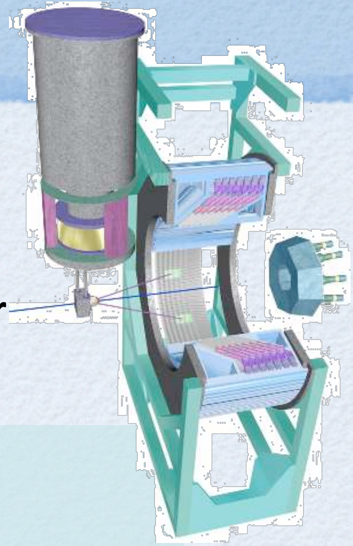
open geometry, integrating

G_M^s, (G_A) at $Q^2 = 0.1$ GeV^2

A4

Open geometry

Fast counting calorimeter for background rejection



$G_E^s + 0.23\, G_M^s$ at $Q^2 = 0.23$ GeV^2

$G_E^s + 0.10\, G_M^s$ at $Q^2 = 0.1$ GeV^2

G_M^s, G_A^e at $Q^2 = 0.23$ GeV^2

HAPPEX

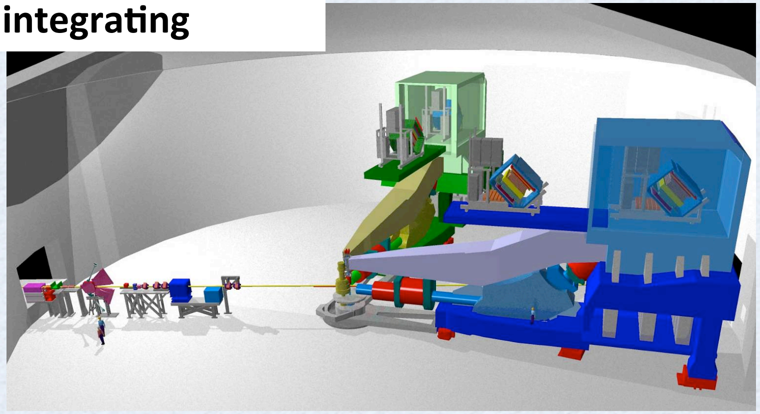
Precision spectrometer, integrating

$G_E^s + 0.39\, G_M^s$ at $Q^2 = 0.48$ GeV^2

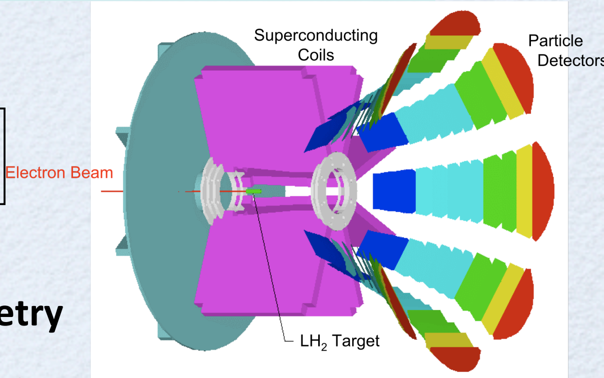
$G_E^s + 0.08\, G_M^s$ at $Q^2 = 0.1$ GeV^2

G_E^s at $Q^2 = 0.1$ GeV^2 (^{4}He)

$G_E^s + 0.48\, G_M^s$ at $Q^2 = 0.62$ GeV^2



G0



Open geometry

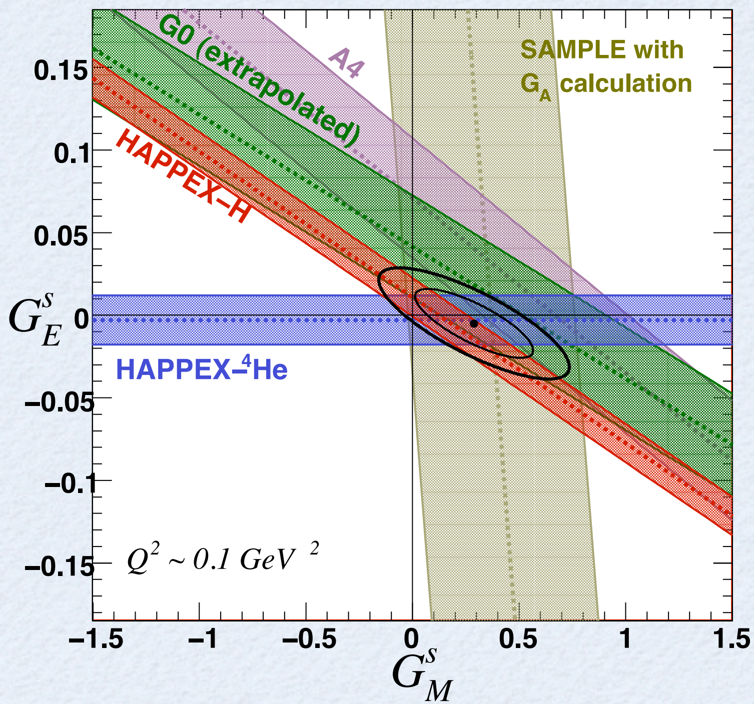
Fast counting with magnetic spectrometer + TOF for background rejection

$G_E^s + \eta\, G_M^s$ over $Q^2 = [0.12,1.0]$ GeV^2

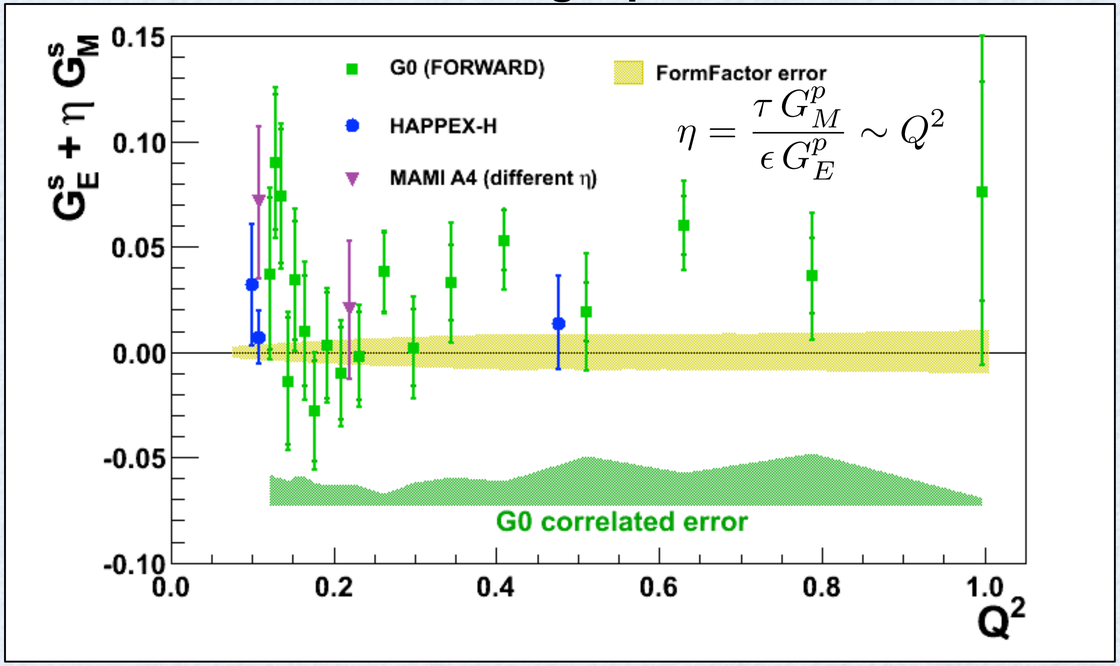
G_M^s, G_A^e at $Q^2 = 0.23, 0.62$ GeV^2

World Data as of Fall 2010

all low Q^2 data



all forward-angle proton data



At Q^2=~0.1 GeV^2,

~3% +/- 2.3% of G_M^P

~0.2 +/- 0.5% of G_E^P

Published fits:

R. Young et al., Phys. Rev. Lett 97, 102002 (2006);

J.Liu et al., Phys. Rev. C 76, 025202 (2007)

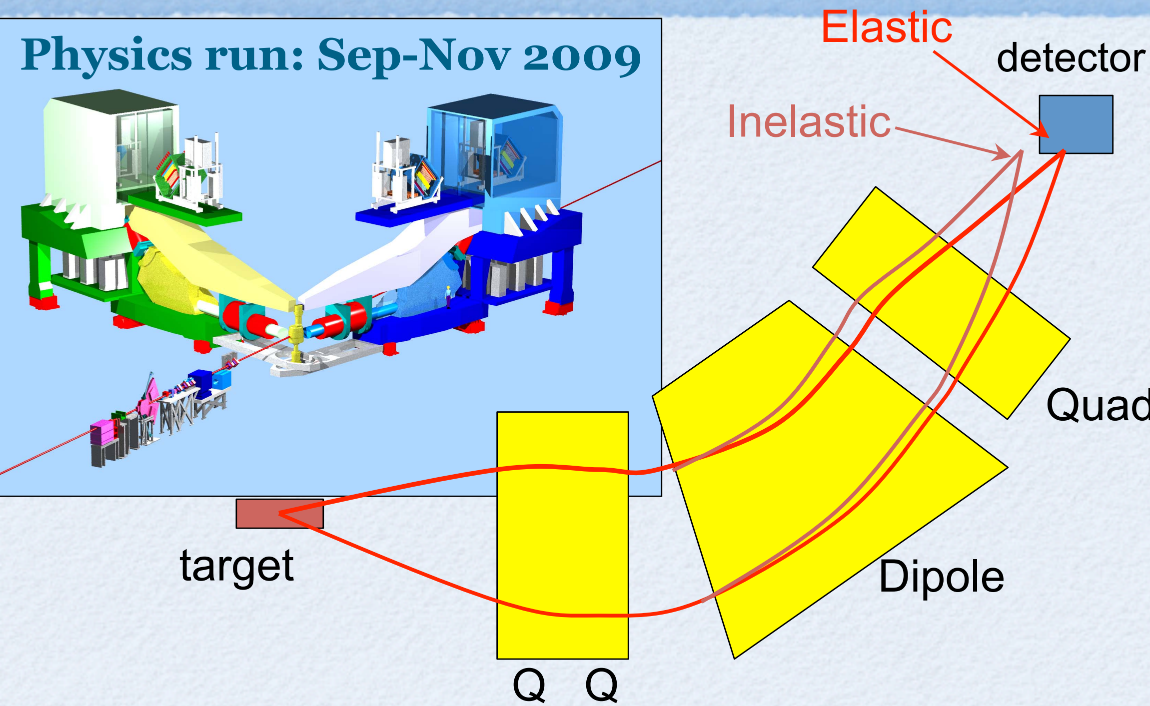
Possible non-zero strange form factor at Q^2 ~ 0.5 GeV^2?

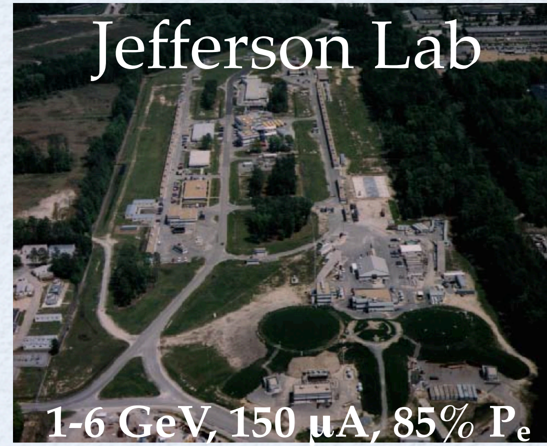
Hall A at Jefferson Laboratory

New Result from HAPPEXIII

$E = 3.3$ GeV, $\theta_{lab} = 14^o$, 100 μA with 85% P_e

Physics run: Sep-Nov 2009





2013: Energy Upgrade to 12 GeV

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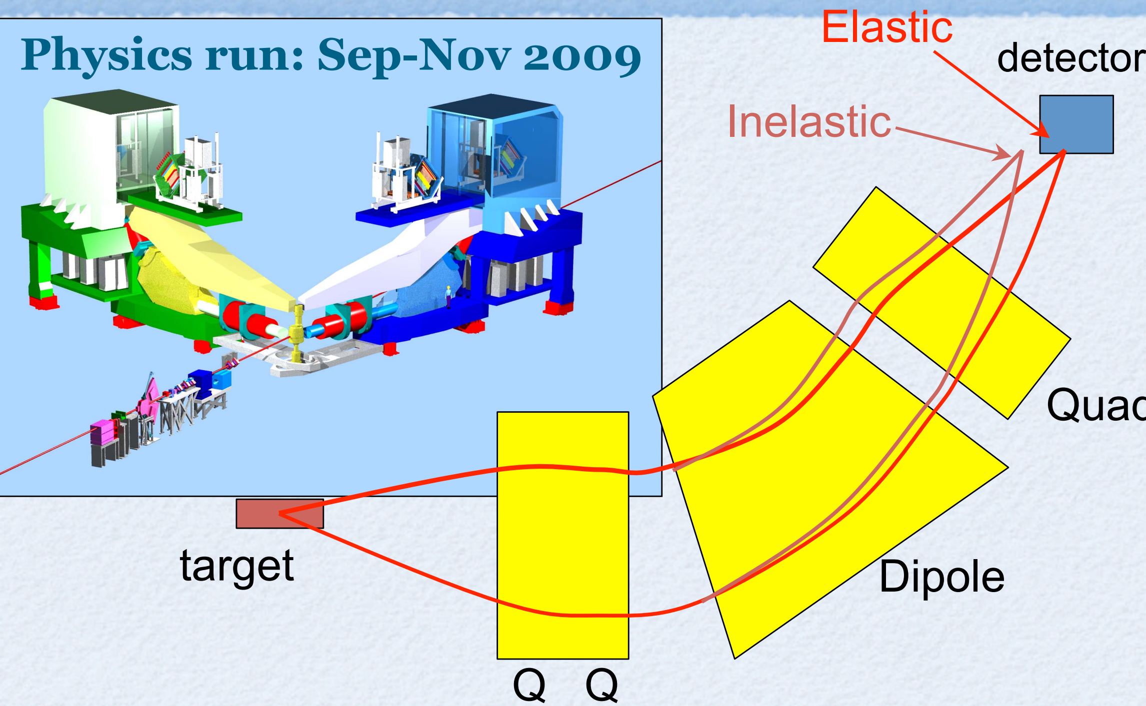

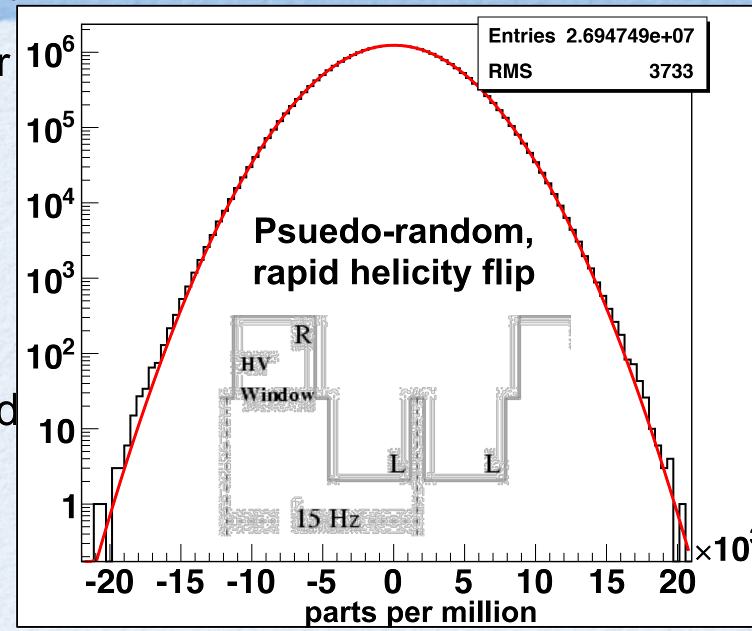

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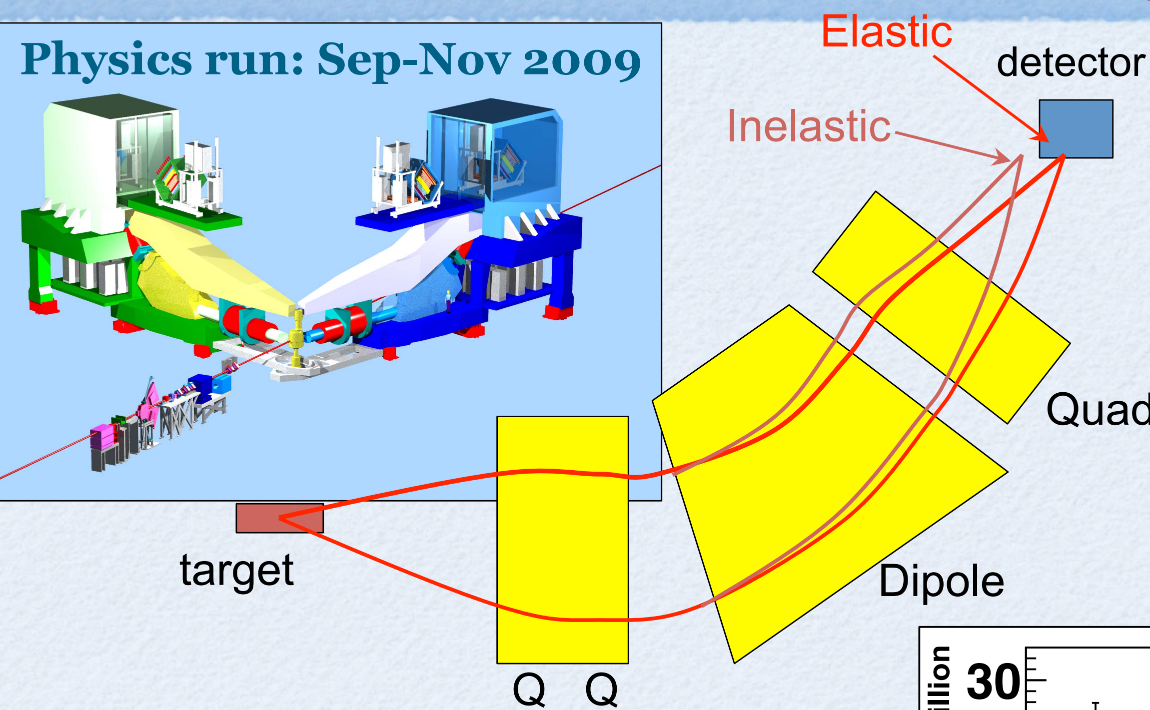
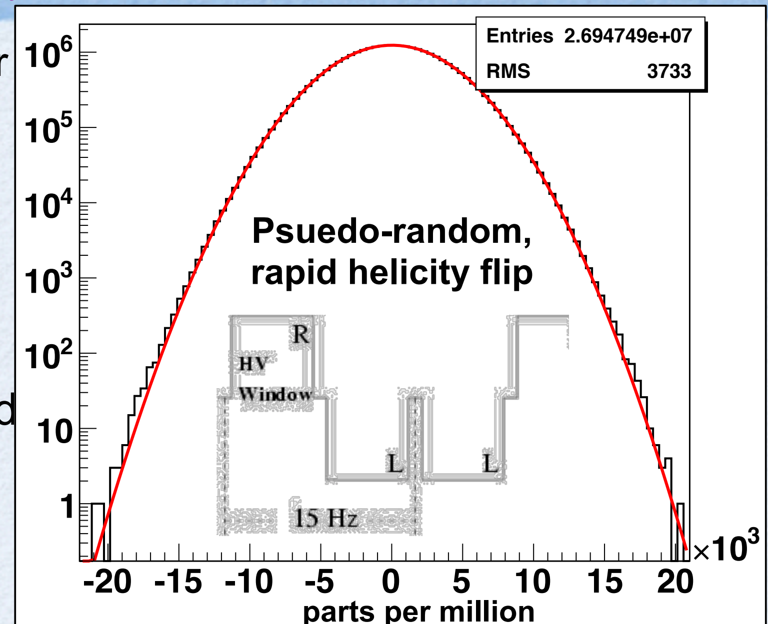




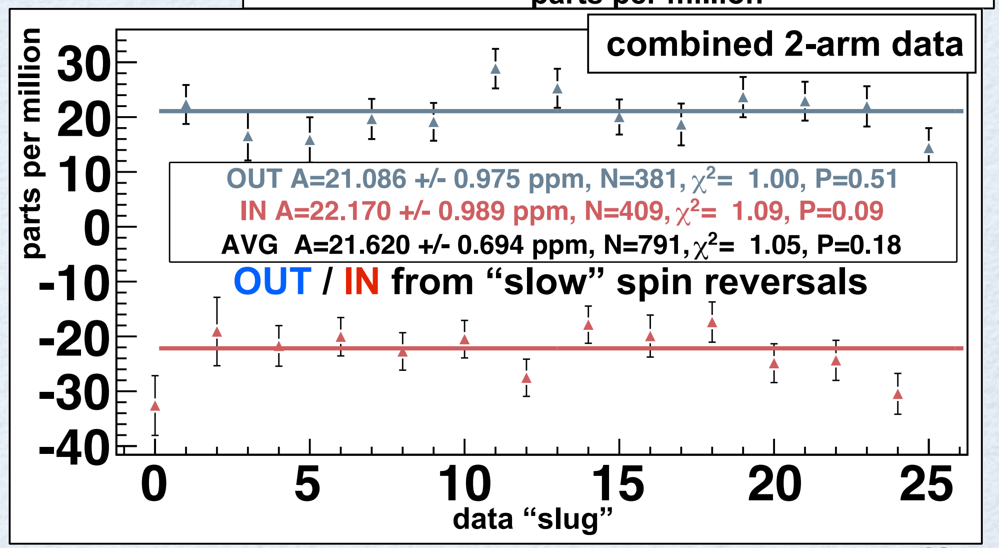
$A_{RAW} = -21.591 \pm 0.688$ (stat) ppm

This includes

- **beam asymmetry correction (-0.01 ppm)**
- **charge normalization (0.20 ppm)**

3.26% (stat)± 1.49% (syst)

total correction ~2.5% + polarization



Result & Perspective

Result submitted to PRL: arXiv:1107.0913

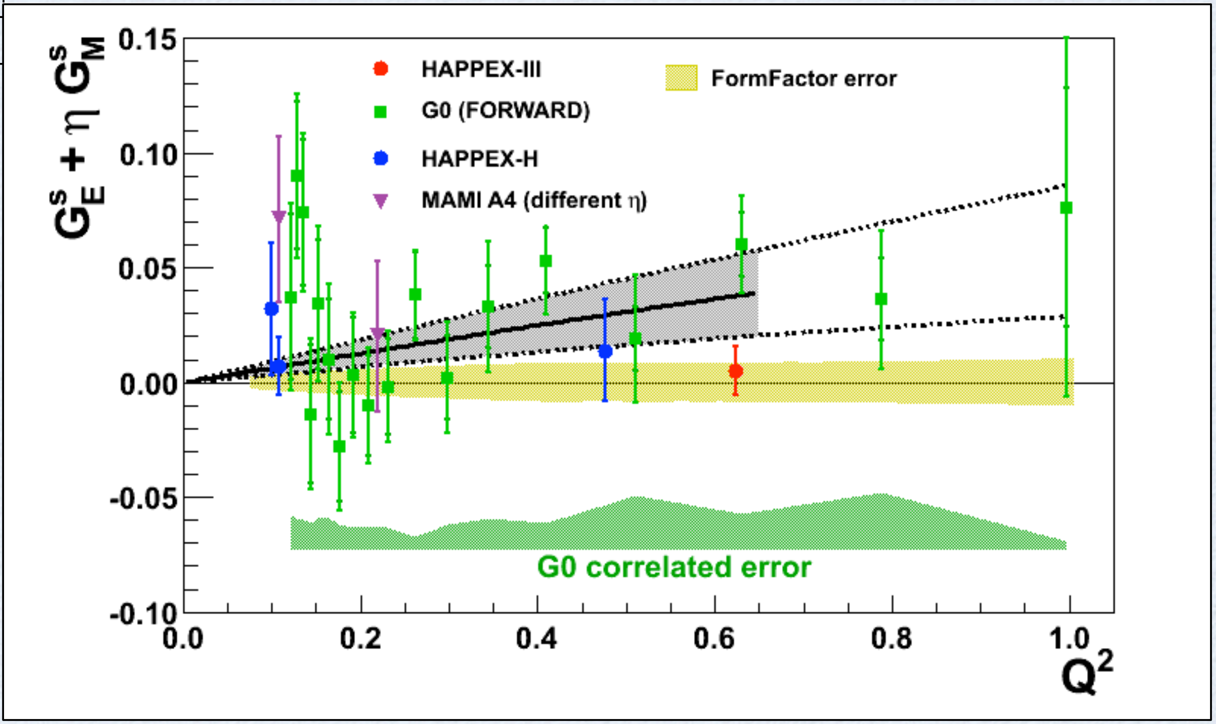
	δA_{PV} (ppm)	$\delta A_{PV} / A_{PV}$
Polarization	0.202	0.85%
Q^2 Measurement	0.160	0.67%
Backgrounds	0.194	0.82%
Linearity	0.129	0.54%
Finite Acceptance	0.048	0.20%
False Asymmetries	0.041	0.17%
Total Systematic	0.353	1.49%
Statistics	0.776	3.27%
Total Experimental	0.853	3.59%

$$A_{PV} = -23.742 \pm 0.776 \text{ (stat)} \pm 0.353 \text{ (syst) ppm}$$

$$Q^2 = 0.6241 \pm 0.0028 \text{ (GeV/c)}^2$$

$$A(G^s=0) = -24.158 \text{ ppm} \pm 0.663 \text{ ppm}$$

$$G^s_E + 0.52\, G^s_M = 0.005 \pm 0.010_{(stat)} \pm 0.004_{(syst)} \pm 0.008_{(FF)}$$



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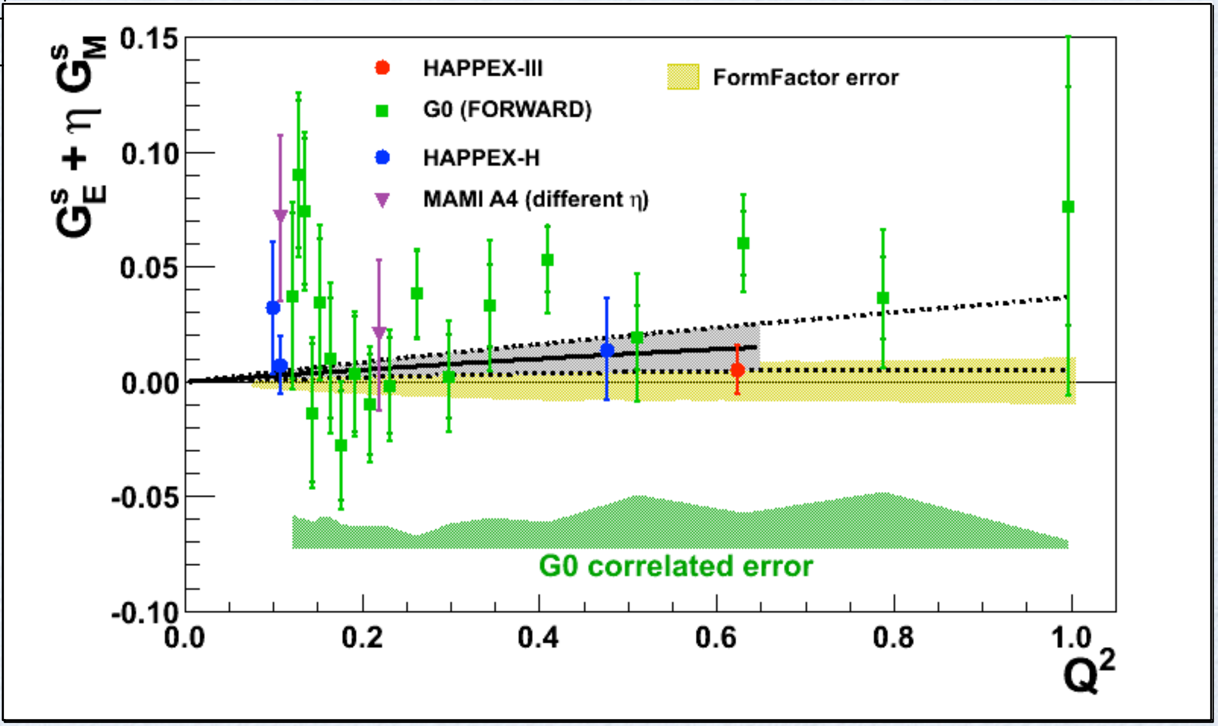

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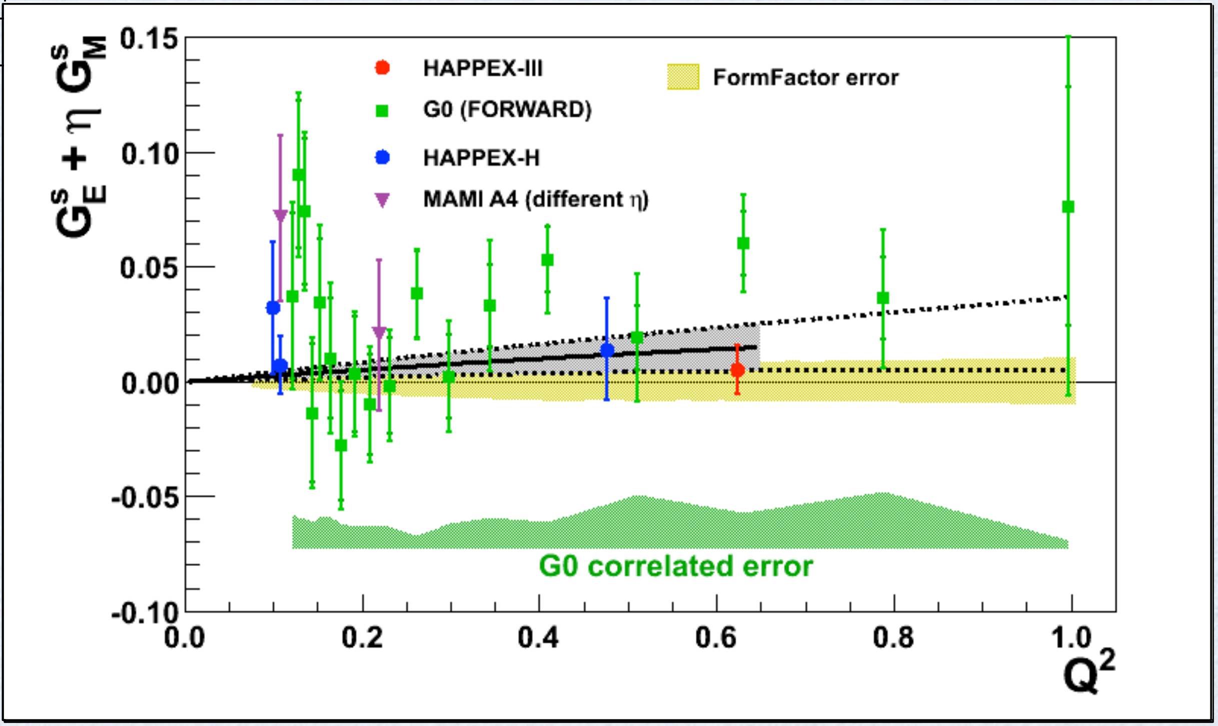
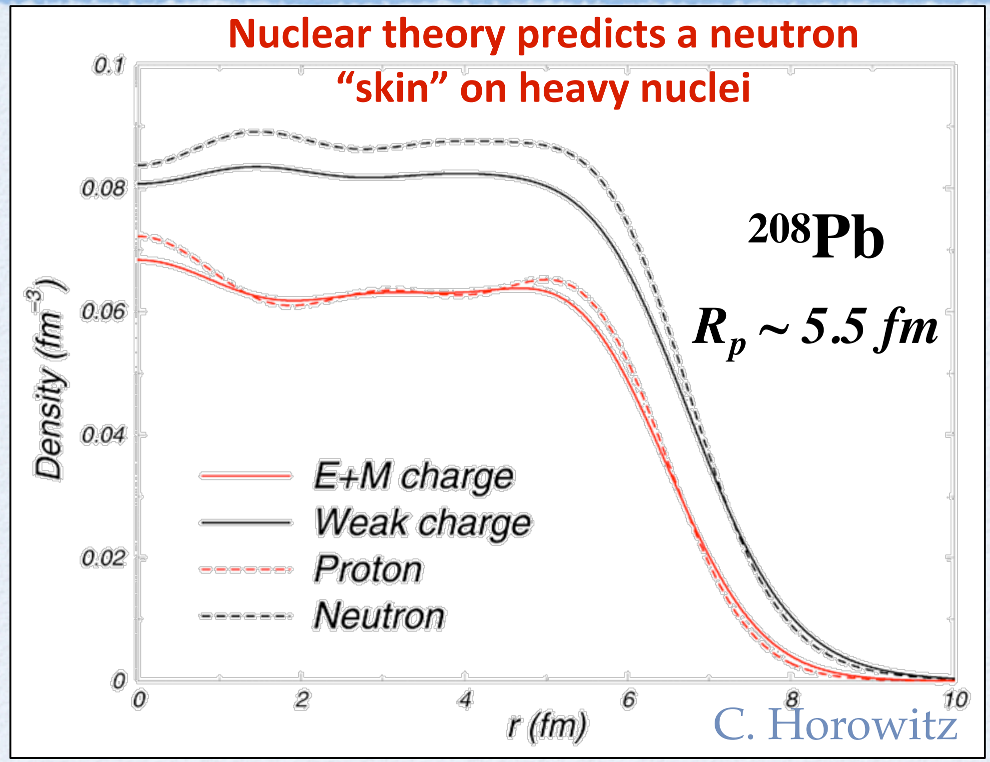


The small size of strange vector matrix elements are in line with modern calculations, especially with input from lattice QCD

Nuclear Weak Density

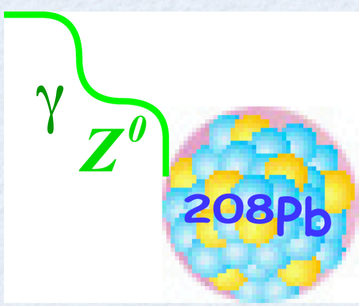


Neutron distribution is not readily accessible to the charge-sensitive photon probe.

$Q^p_{EM} \sim 1$ $\quad$ $Q^n_{EM} \sim 0$

$Q^n_W \sim 1$ $\quad$ $Q^p_W \sim 1 - 4\sin^2\theta_W$

	proton	neutron
Electric charge	1	0
Weak charge	~0.08	1



$$M^{EM} = \frac{4\pi\alpha}{Q^2} F_p(Q^2)$$

$$M^{NC}_{PV} = \frac{G_F}{\sqrt{2}}\left[\left(1 - 4\sin^2\theta_W\right)F_p(Q^2) - F_n(Q^2)\right]$$

$$A_{PV} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{F_n(Q^2)}{F_p(Q^2)}$$

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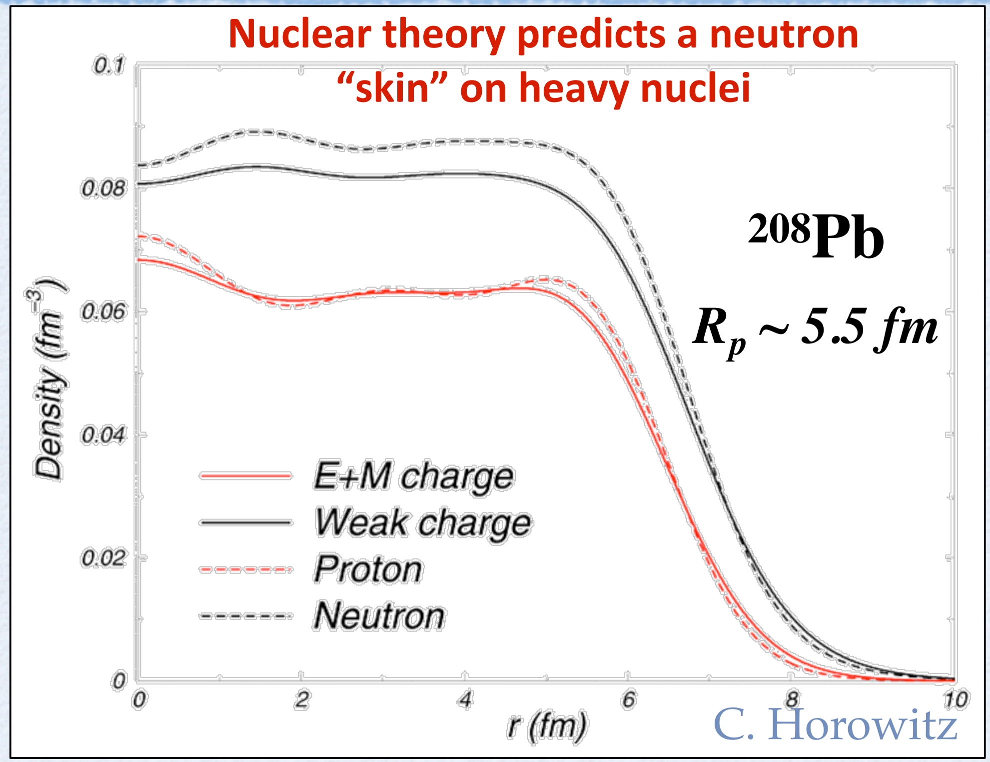

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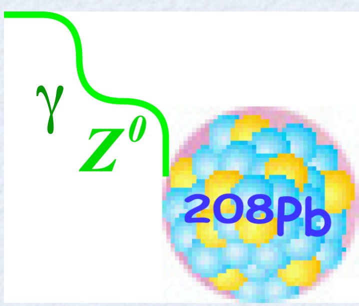
PREX (Pb-Radius EXperiment)

$Q^2 \sim 0.01\ GeV^2$ ⇨ **$A_{PV} \sim 0.6$ ppm**

5^o scattering angle $\qquad$ **Rate ~1.5 GHz**



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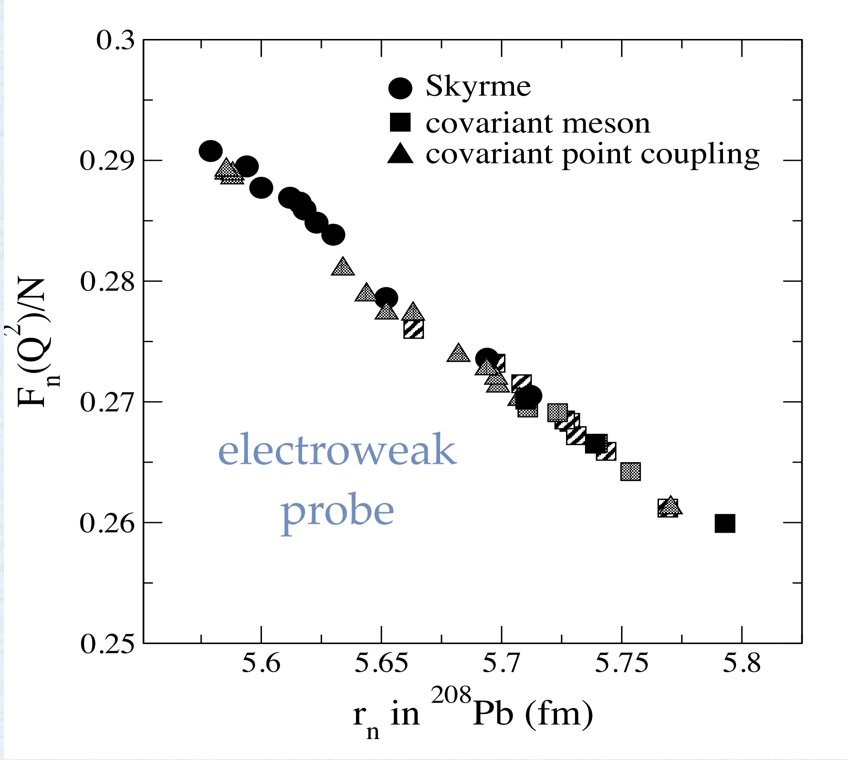
Neutron Radius Information

- Proton-Nucleus Elastic
- Pion, alpha, d Scattering
- Pion Photoproduction
- Heavy ion collisions
- Rare Isotopes (dripline)

Involve strong probes

A single measurement of F_n translates to a measurement of R_n via mean-field nuclear models

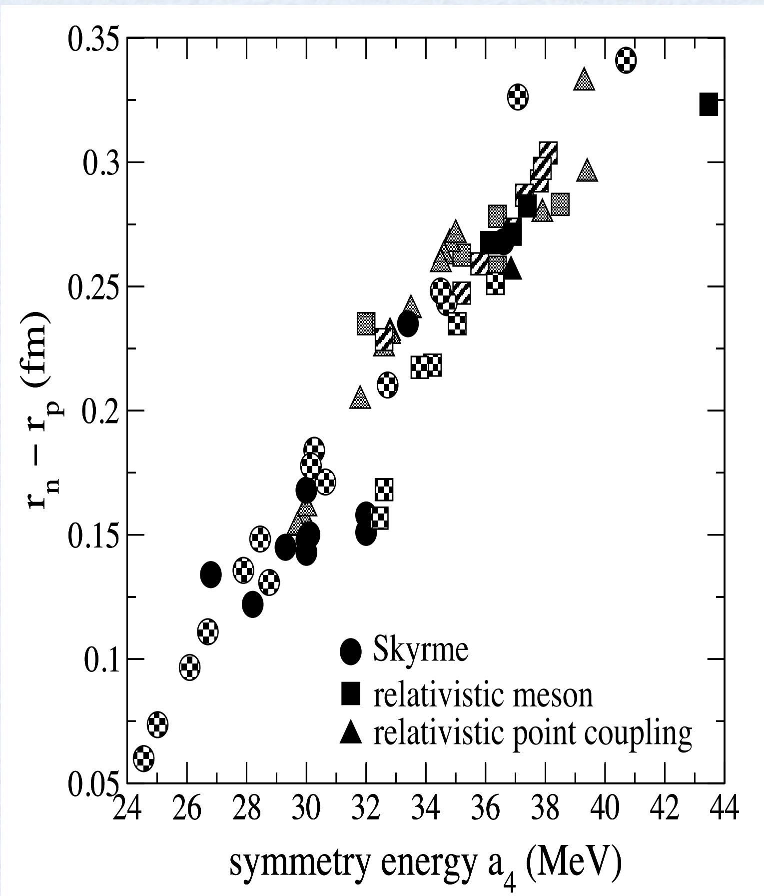


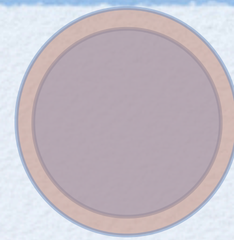
- PREX $\longrightarrow$ ***Electroweak probe***

- Theory $\longrightarrow$ ***MFT fit mostly by data other than neutron densities***

Several Applications

…and measuring r_N pins down the symmetry energy





neutron skin

Several Applications

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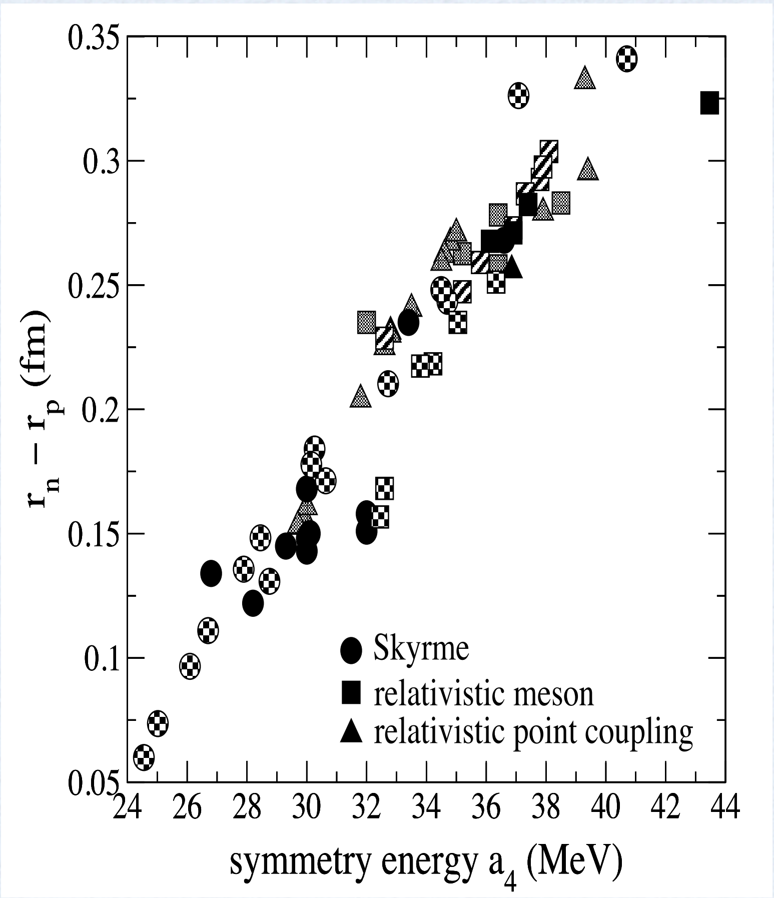

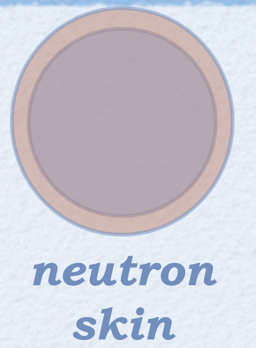

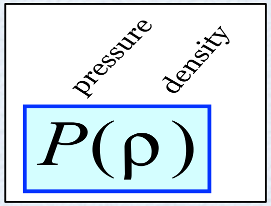

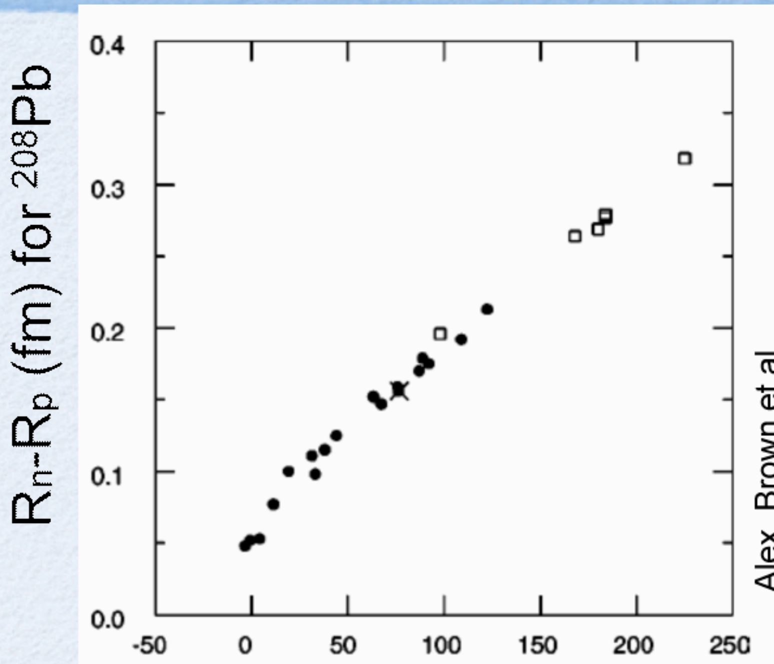

Neutron matter P (MeV/fm^3) x100 at a density of 0.1 fm^{-3}.

Several Applications

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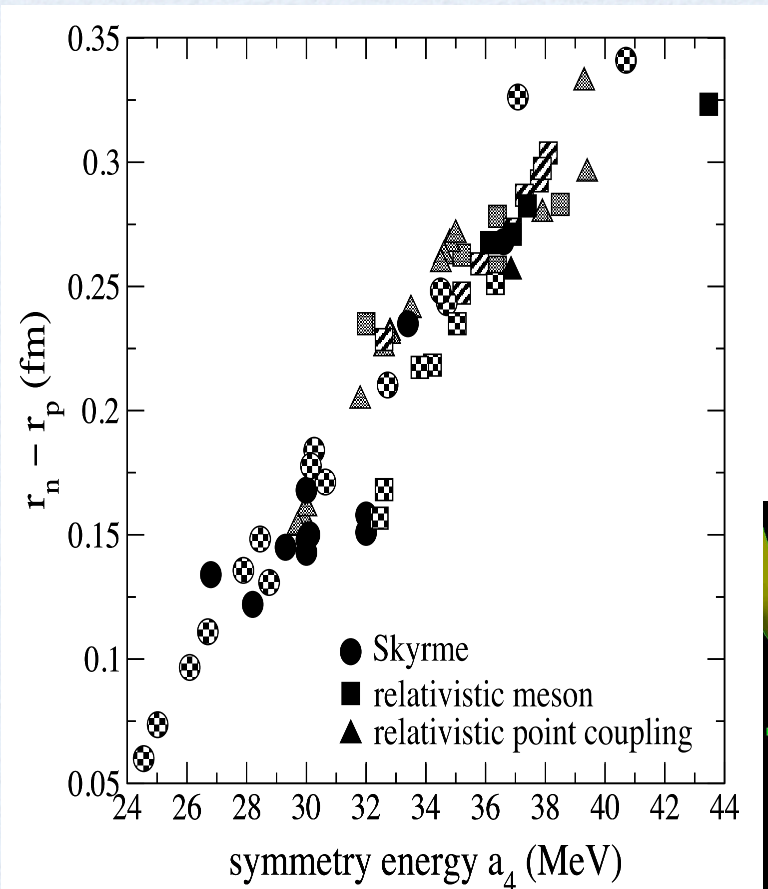

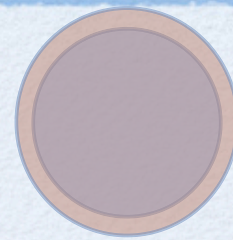

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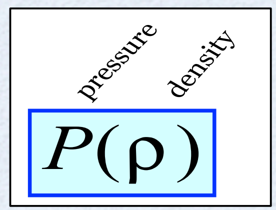
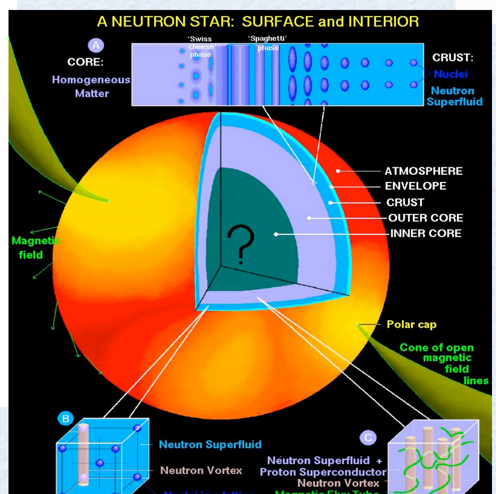
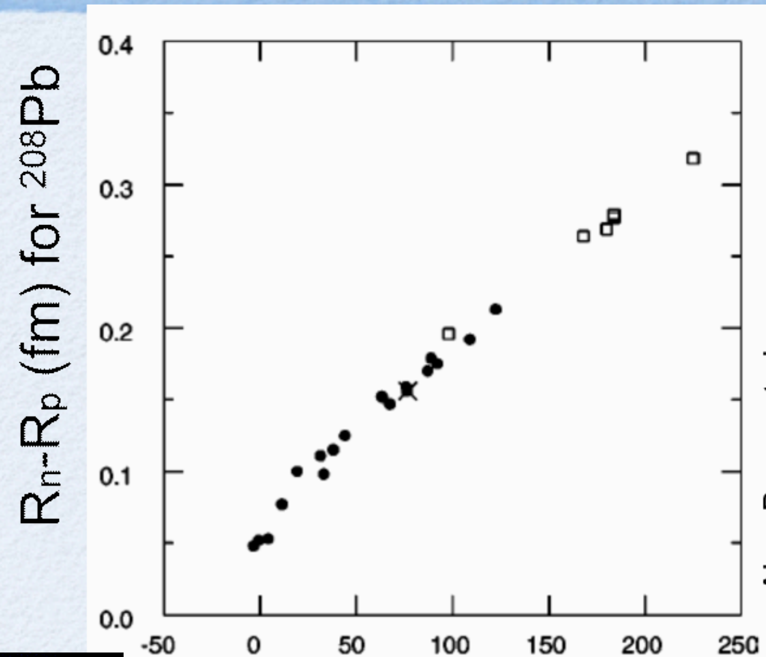






Neutron matter P (MeV/fm^3) x100 at a density of 0.1 fm^{-3}.

R_n calibrates the equation of state of neutron rich matter

Implications for neutron star structure

PREX at JLab

preliminary result

PREX run: March-June 2010

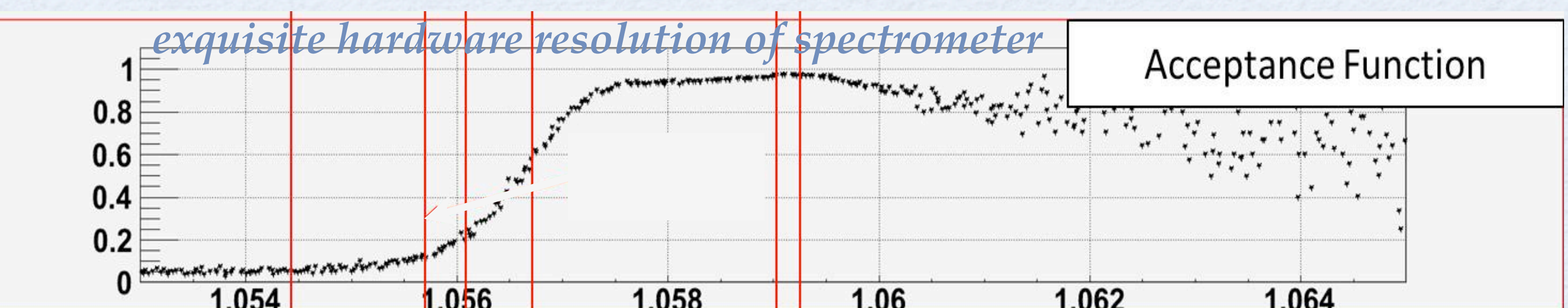
$Q^2 \sim 0.01\ GeV^2$ ⟹ **$A_{PV} \sim 0.5$ ppm**

$\delta(A_{PV}) \sim 3\%$

$\delta(R_p\text{-}R_n) \sim (4\pm1\%)\ R_p$

$\delta(A_{PV}) \sim 15$ ppb!

Models and global fits
range from 1 to 6%



C 1st excited state

4^- 5^- 3^-
Pb excited states

C Pb
Ground States

Momentum (GeV/c)

Detector integrates the elastic peak
Backgrounds from inelastics suppressed

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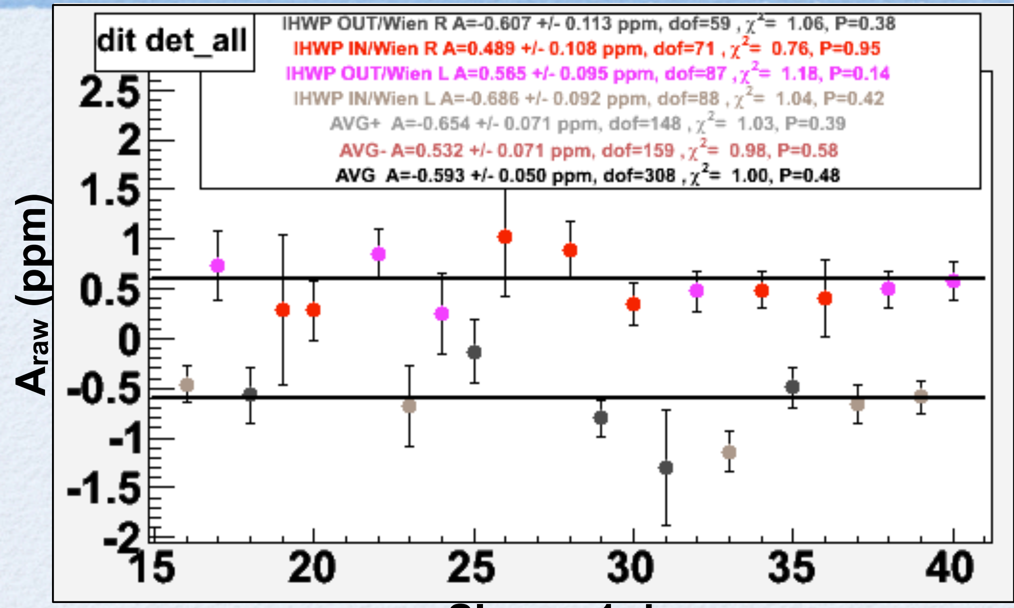
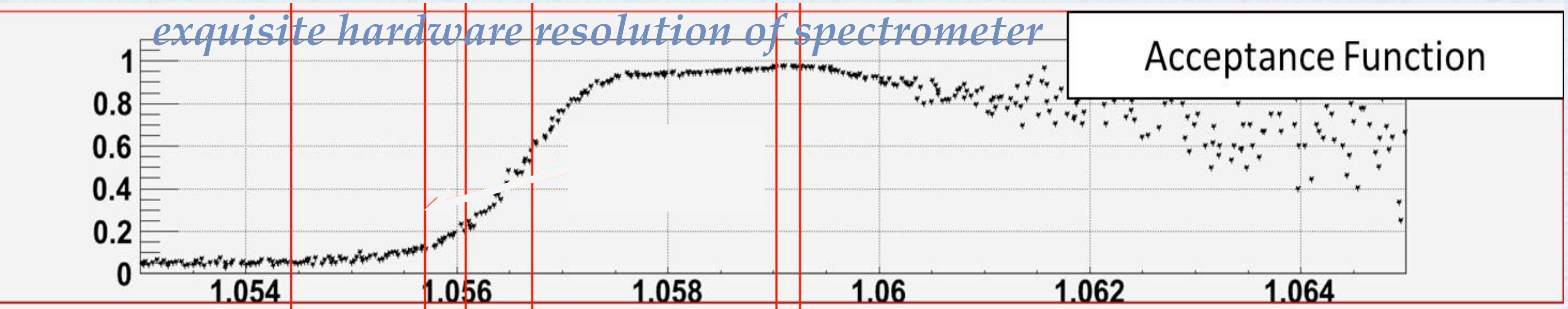


Slug ~ 1 day



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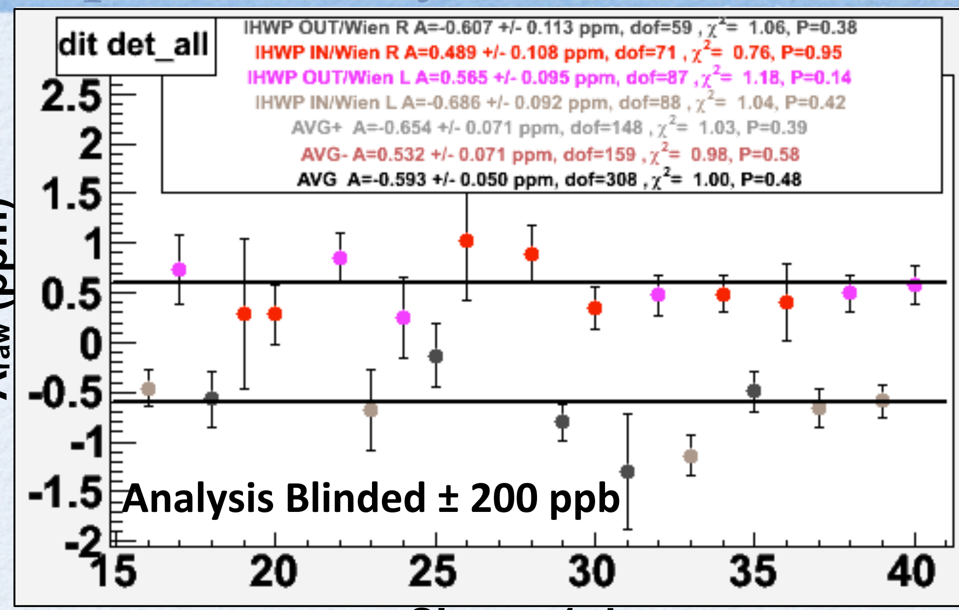

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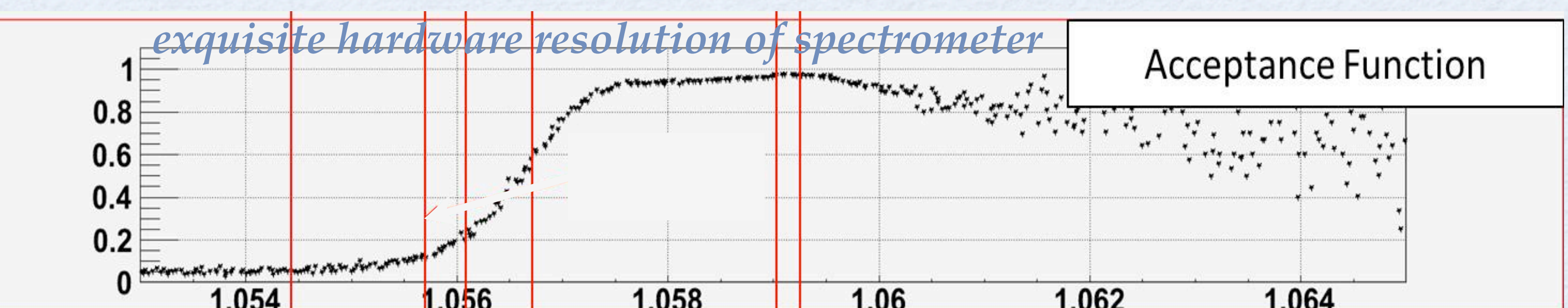

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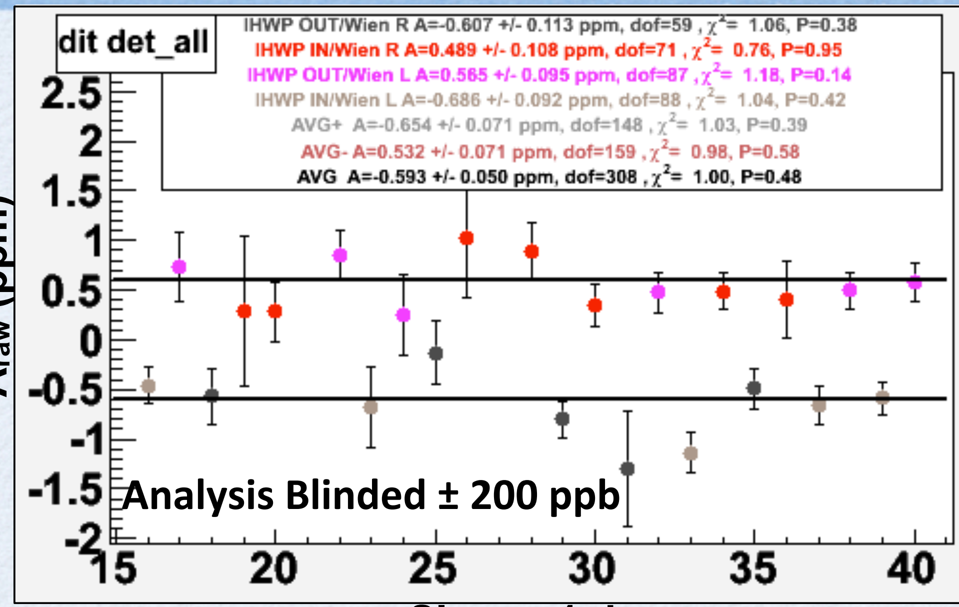

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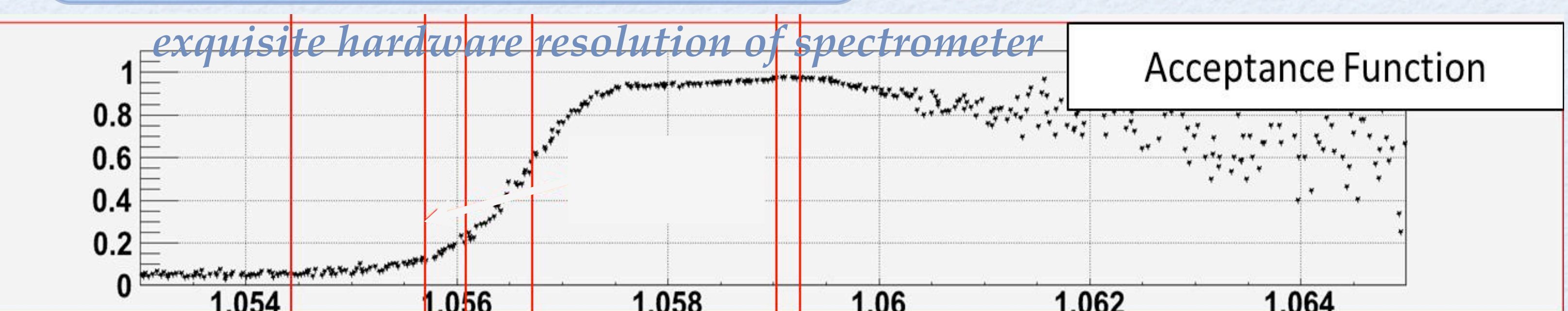

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Result and Outlook

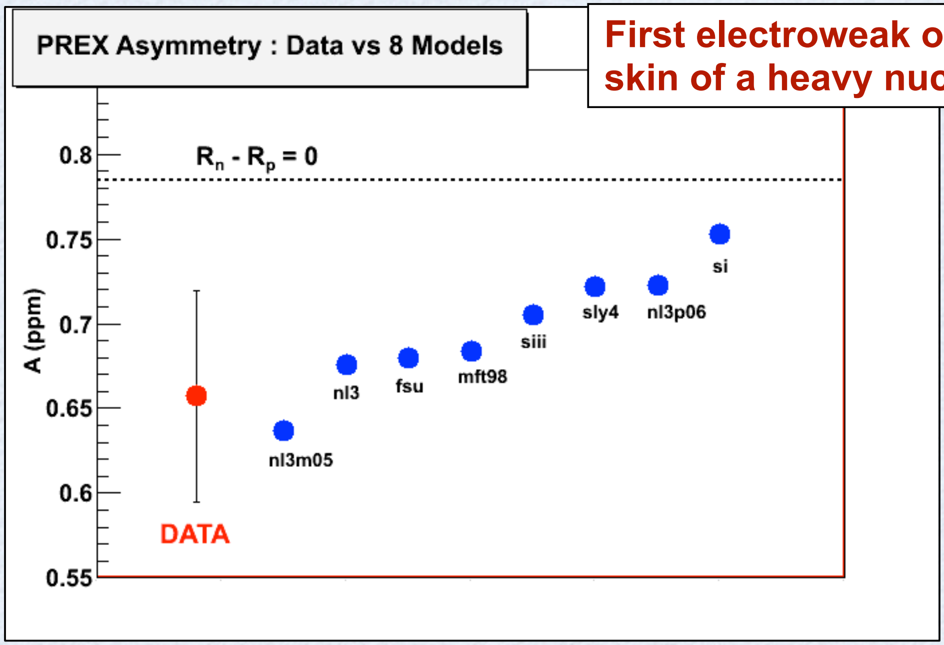
A_{PV} = $0.6571 \pm 0.0604(stat) \pm 0.0130(syst)$ ppm

9.2 % 2.0 %

Neutron Skin = R_N - R_P
= 0.34 + 0.15 - 0.17 fm

Preliminary estimate from C.J. Horowitz

PRL in preparation



First electroweak observation of the neutron skin of a heavy nucleus (CL =95%)

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PRL in preparation

	E (GeV)	Rate (MHz @ 50 µA)	APV (ppm)	days to 1% on R_n
^{208}Pb	1.05	1700	0.6	30
^{120}Sn	1.25	810	1.1	20
^{48}Ca	1.7	270	2.5	12
	2.2	15	2.8	18

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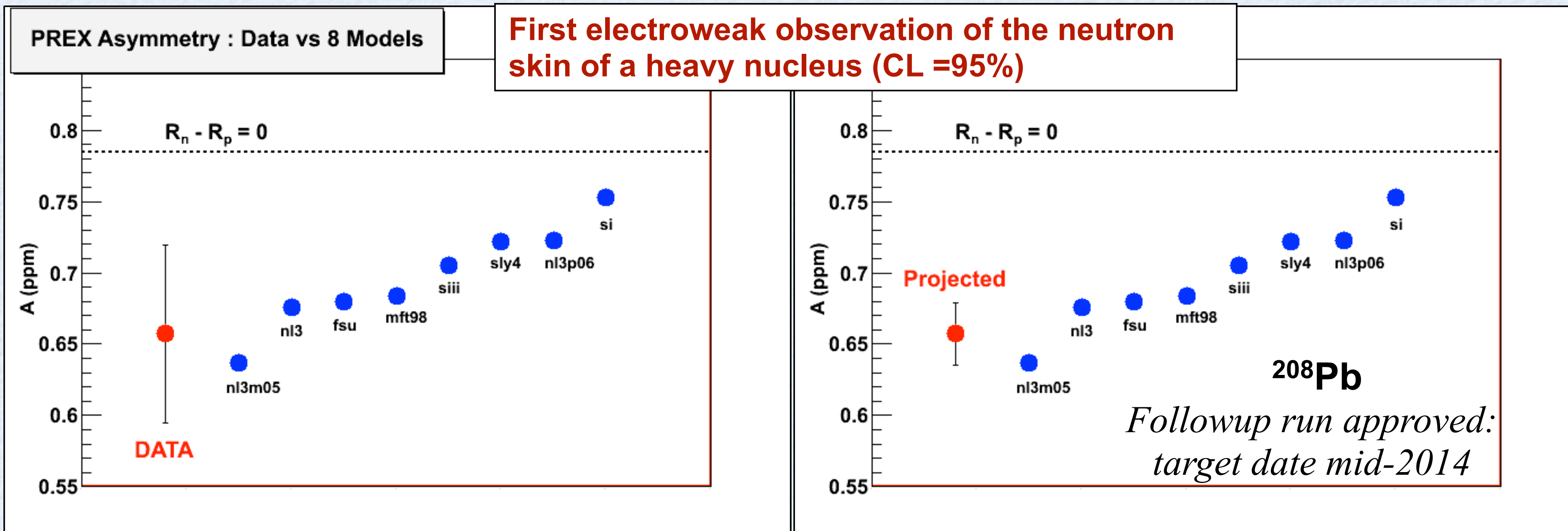

50's & 60's: Electron Scattering probed nuclear and nucleon substructure

70's: Parity-violating deep inelastic scattering validated the electroweak theory

90's onwards: Physics ≤ 1 GeV

Precision Tests of the Electroweak Theory

Turn of the century: Physics ~ 1 TeV

turn of the century

Modern Electroweak Physics

Physics up to a length scale of 10^{-18} m well understood but.....

Many questions still unanswered….

- **Why exactly 3 generations of particles?**
- **Why are the W and Z Bosons ~ 100 GeV?**
  - What is so special about 10^{-18} m?
- **What is the origin of mass?**
- **How did matter dominate over anti-matter**
- **Is there a single unifying super-force?**
  - Were there as yet unseen forces in the early universe?
- **Why are neutrinos so light?**
  - Are neutrinos their own anti-particles?
- **What is dark matter and dark energy?**

The High Energy Frontier: Collider Physics

The Cosmic Frontier: Particle, Nuclear and Gravitational Astrophysics

The Intensity Frontier

Direct and Indirect Searches for Physics Beyond the Standard Model

Compelling arguments for "New Dynamics" at the TeV Scale

A comprehensive search for clues requires:

Large Hadron Collider ***as well as*** **Lower Energy: $Q^2 << M_Z^2$**

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- **Violations of Accidental(?) Symmetries**
  - CP, T (EDMs, Decays), CPT, Charged Lepton Flavor, Lepton Number
- **Dark Matter Searches**
- **Neutrino Masses and Mixing**
  - $0\nu\beta\beta$ decay, reactor θ_{13}, long baseline experiments
- **Precision Electroweak Measurements at $Q^2 << M_Z^2$**
  - flavor conserving and flavor changing neutral current amplitudes, charged current amplitudes, muon g-2

Intense beams, ultra-high precision, exotic nuclei, table-top experiments, rare processes....

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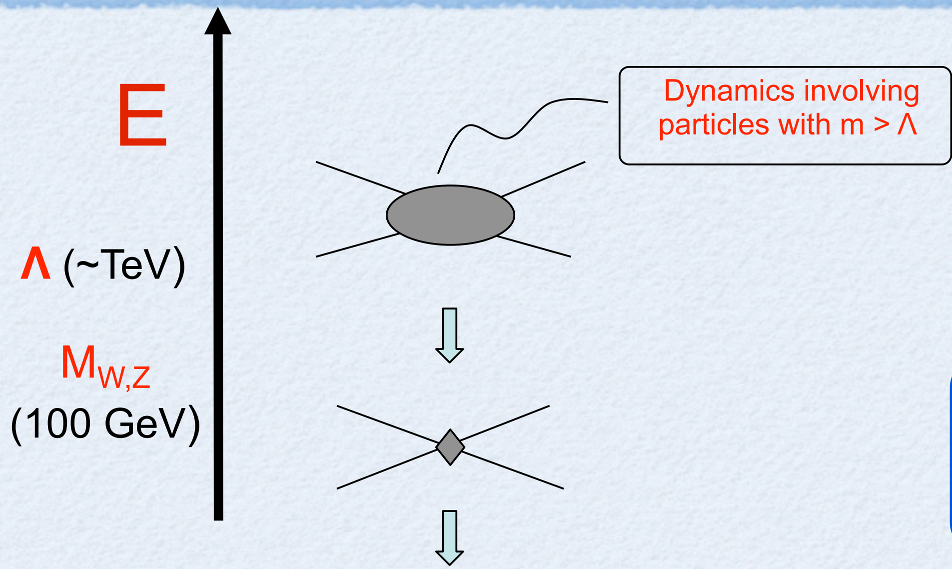
Indirect Clues

Electroweak Interactions at scales much lower than the W/Z mass



Heavy Z's and neutrinos, technicolor, compositeness, extra dimensions, SUSY…

Many theories predict new forces that disappeared when the universe cooled

courtesy
V. Cirigliano
H. Maruyama

$\mathcal{L}_{SM+\mathrm{Heavy}}$

$\Downarrow$

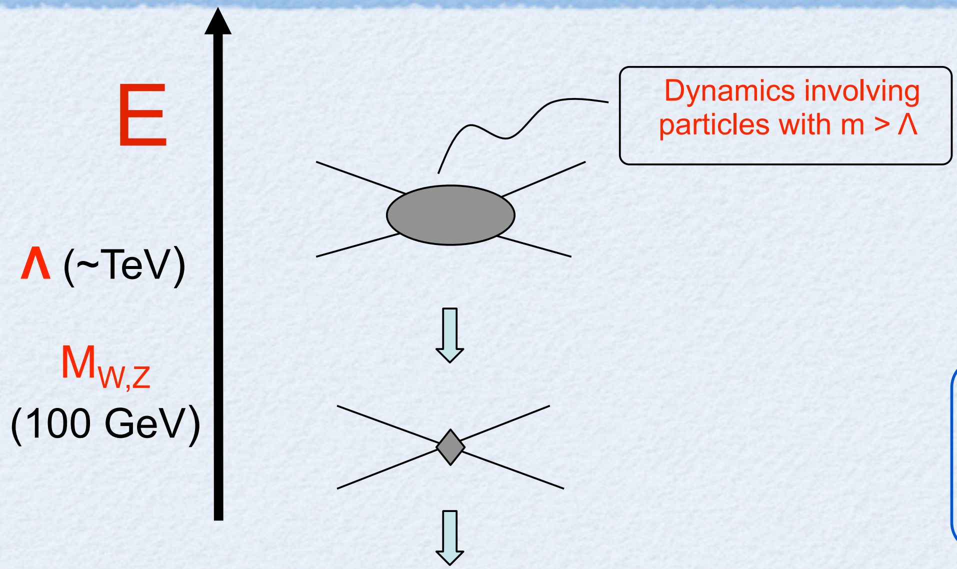
$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

higher dimensional operators can be systematically classified

- ***flavor changing as well as flavor diagonal***
- ***charged current as well as neutral current***

Indirect Clues

Electroweak Interactions at scales much lower than the W/Z mass



Heavy Z's and neutrinos, technicolor, compositeness, extra dimensions, SUSY…

Many theories predict new forces that disappeared when the universe cooled

courtesy
V. Cirigliano
H. Maruyama

$\mathcal{L}_{SM+\mathrm{Heavy}}$

$\Downarrow$

$$\boxed{\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots}$$

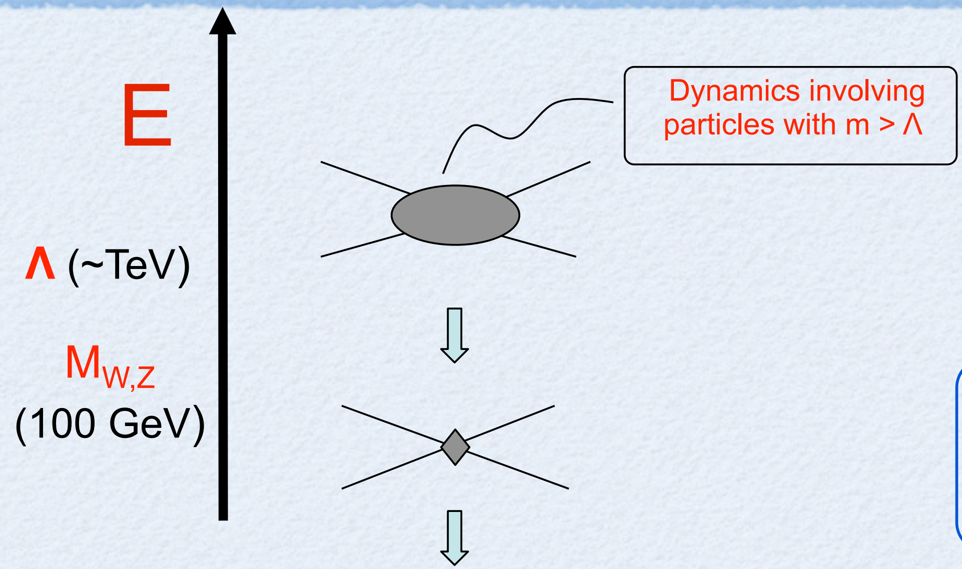
higher dimensional operators can be systematically classified

- ***flavor changing as well as flavor diagonal***
- ***charged current as well as neutral current***

Measurements with the potential to indirectly access the TeV scale involve pushing one or more experimental parameters to the extreme such as intensity, luminosity, volume, radio-purity, precision, accuracy....

Indirect Clues

Electroweak Interactions at scales much lower than the W/Z mass



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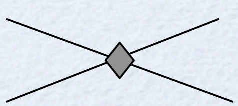
new contact interactions



$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

must reach Λ ~ several TeV

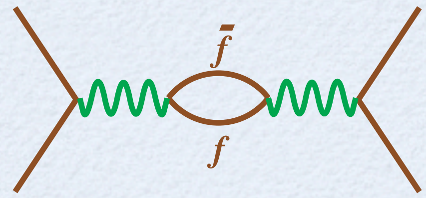
EW Quantum Corrections

Precision Measurements of Electroweak (EW) Couplings

For electroweak interactions, 3 input parameters needed:

1. **electron g-2 anomaly**
2. **The muon lifetime**
3. **The Z line shape**

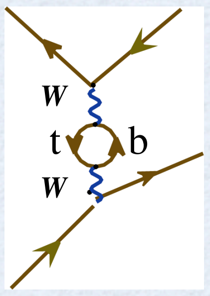
higher order terms in the perturbative expansion



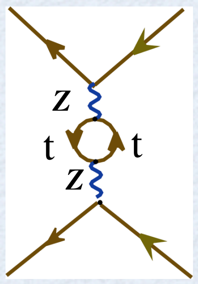
effective charge increases with decreasing distance:

4th and 5th best measured parameters: M_W and $\sin^2\theta_W$

predicted values differ from tree level predictions: indirect access to “heavy” physics



Muon decay



Z production

EW Quantum Corrections

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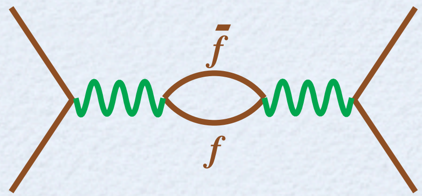

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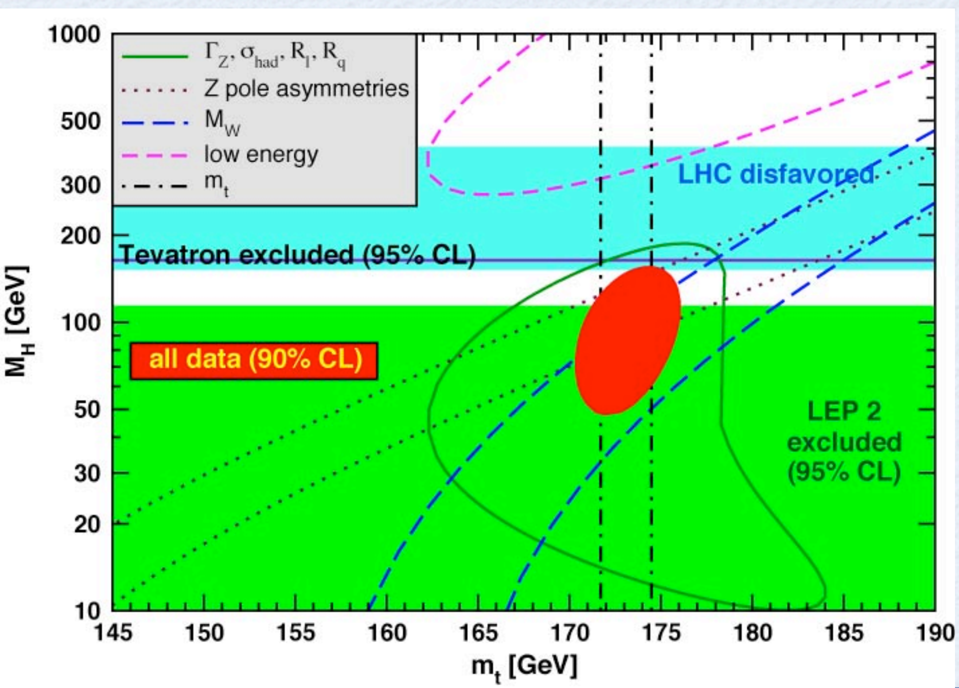
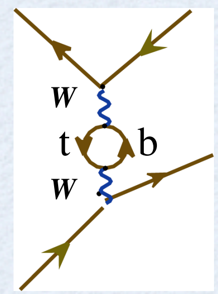
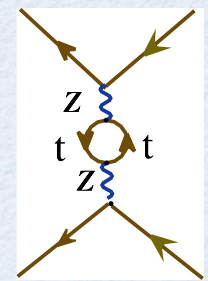




Muon decay



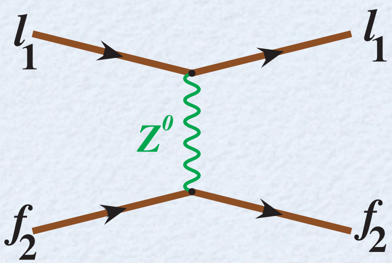
Z production

Known "heavy" physics: the top quark

Assumed "heavy physics": the Higgs boson

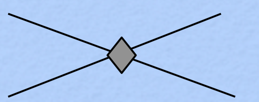
Low Q² Neutral Currents

Search for New Flavor Conserving Contact Interactions



amplitudes can be very precisely predicted

Allows searches for new physics at the TeV scale via small measurement deviations



$$\frac{1}{\Lambda^2}\mathcal{L}_6$$

All flavor-conserving weak neutral current amplitudes are functions of $\sin^2\theta_W$

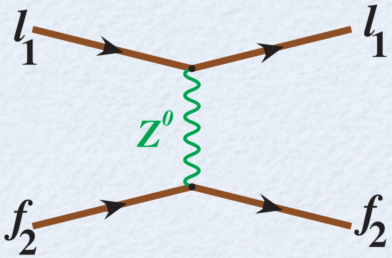
*sensitive to **TeV-scale contact interactions** iff:*

- ***$\delta(\sin^2\theta_W) \leq 0.5\%$***
- ***away from the Z resonance***

- **Precision Neutrino Scattering**
- **New Physics/Weak-Electromagnetic Interference**
  - *opposite parity transitions in heavy atoms*
  - *parity-violating electron scattering*

Low Q^2 Neutral Currents

Search for New Flavor Conserving Contact Interactions



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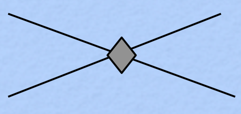

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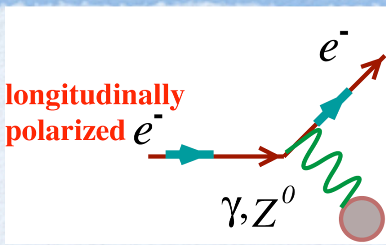
Electromagnetic amplitude interferes with Z-exchange as well as any new physics

$$\left|\mathbf{A}_\gamma + \mathbf{A_Z} + \mathbf{A}_{\text{new}}\right|^2 \rightarrow \mathbf{A}_\gamma^2\left[\mathbf{1} + \mathbf{2}\left(\frac{\mathbf{A_Z}}{\mathbf{A}_\gamma}\right) + \mathbf{2}\left(\frac{\mathbf{A}_{\text{new}}}{\mathbf{A}_\gamma}\right)\right]$$

The Electron's Weak Charge

Parity-violating Electron Scattering



$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha}\left(g_A^e \boxed{g_V^T} + \beta\, g_V^e g_A^T\right)$$

g_V and g_A are function of $\sin^2\theta_W$

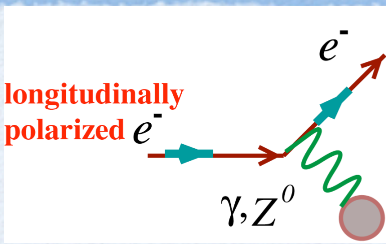
Weak Charge Q_W

electron & proton target: $\mathbf{Q_W = 1 - 4\sin^2\theta_W}$ **highly suppressed**

~ 1999: electron-electron weak attractive force had never been measured!

The Electron's Weak Charge

Parity-violating Electron Scattering



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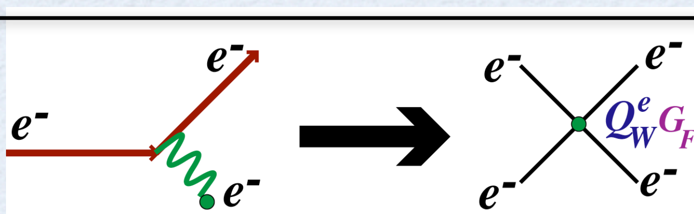
g_V and g_A are function of $\sin^2\theta_W$

Weak Charge Qw

electron & proton target: $Q_W = 1 - 4\sin^2\theta_W$ highly suppressed



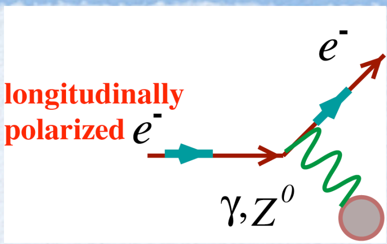
Fixed Target Parity-Violating Møller Scattering

Purely leptonic reaction!

~ 1999: electron-electron weak attractive force had never been measured!

The Electron's Weak Charge

Parity-violating Electron Scattering



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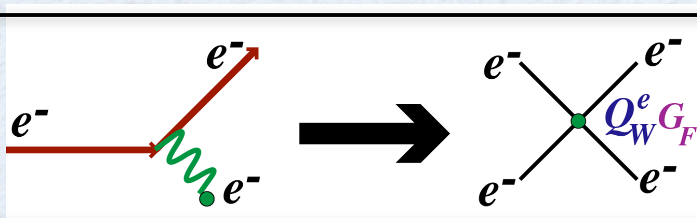

Fixed Target Parity-Violating Møller Scattering
Purely leptonic reaction!

$$A_{PV} \approx 8\times 10^{-8} E_{beam}(1 - 4\sin^2\vartheta_W) \Rightarrow$$ **Tiny!**

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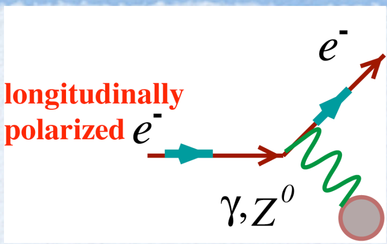
The Electron's Weak Charge

Parity-violating Electron Scattering



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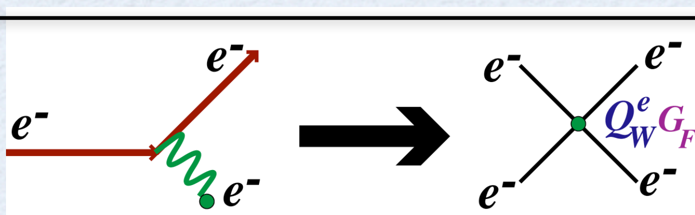

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$$\sigma \propto \frac{1}{E_{lab}} \Rightarrow$$ *Figure of Merit rises linearly with E_{lab}*

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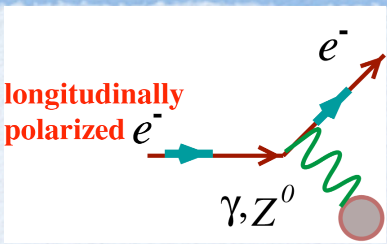
The Electron's Weak Charge

Parity-violating Electron Scattering



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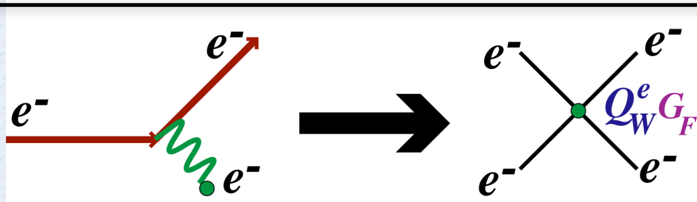

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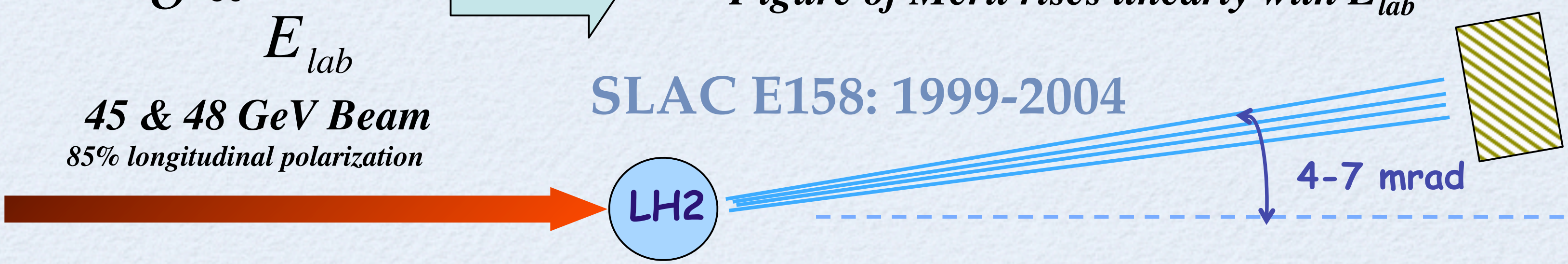
$$\sigma \propto \frac{1}{E_{lab}}$$ *Figure of Merit rises linearly with E_{lab}*

45 & 48 GeV Beam

85% longitudinal polarization

SLAC E158: 1999-2004

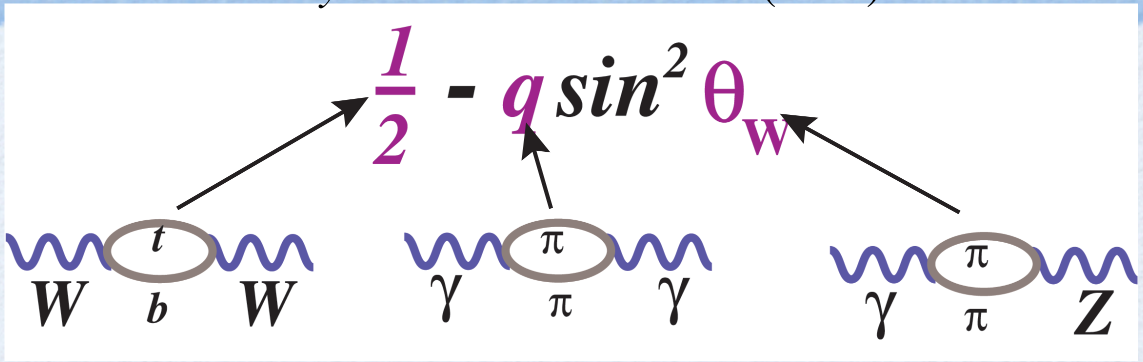


End Station A at the Standord Linear Accelerator Center (SLAC)

$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$

The Legacy of E158

Phys. Rev. Lett. **95** 081601 (2005)



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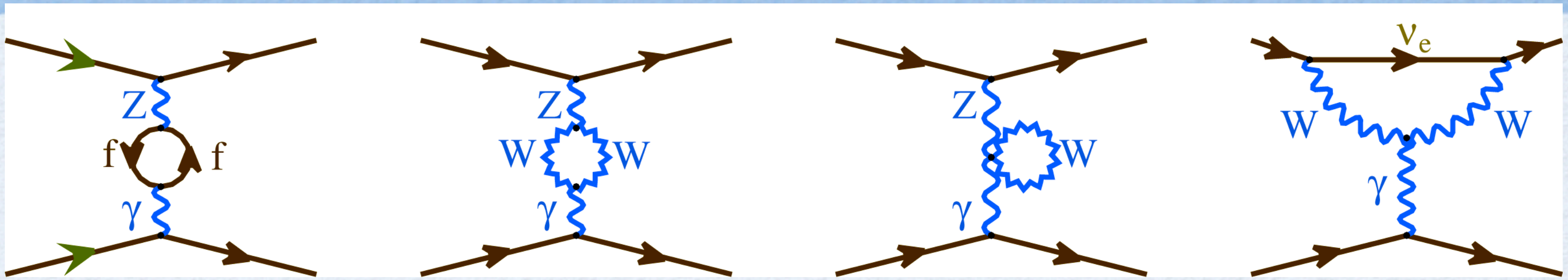

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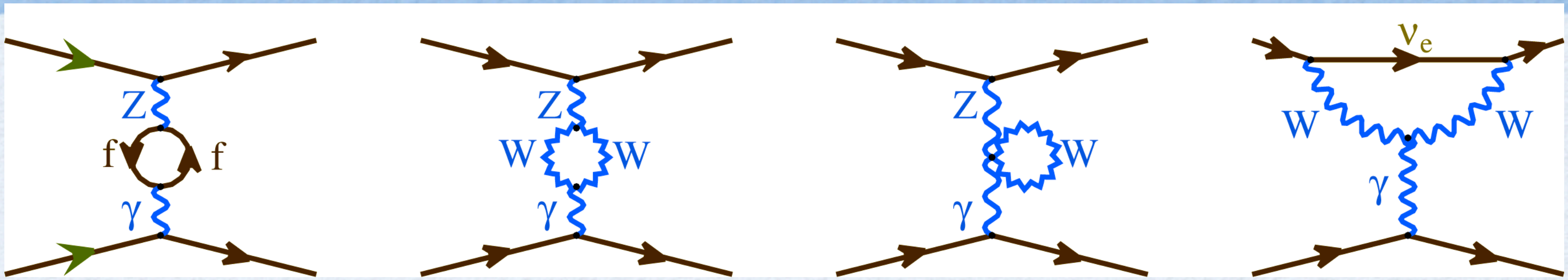

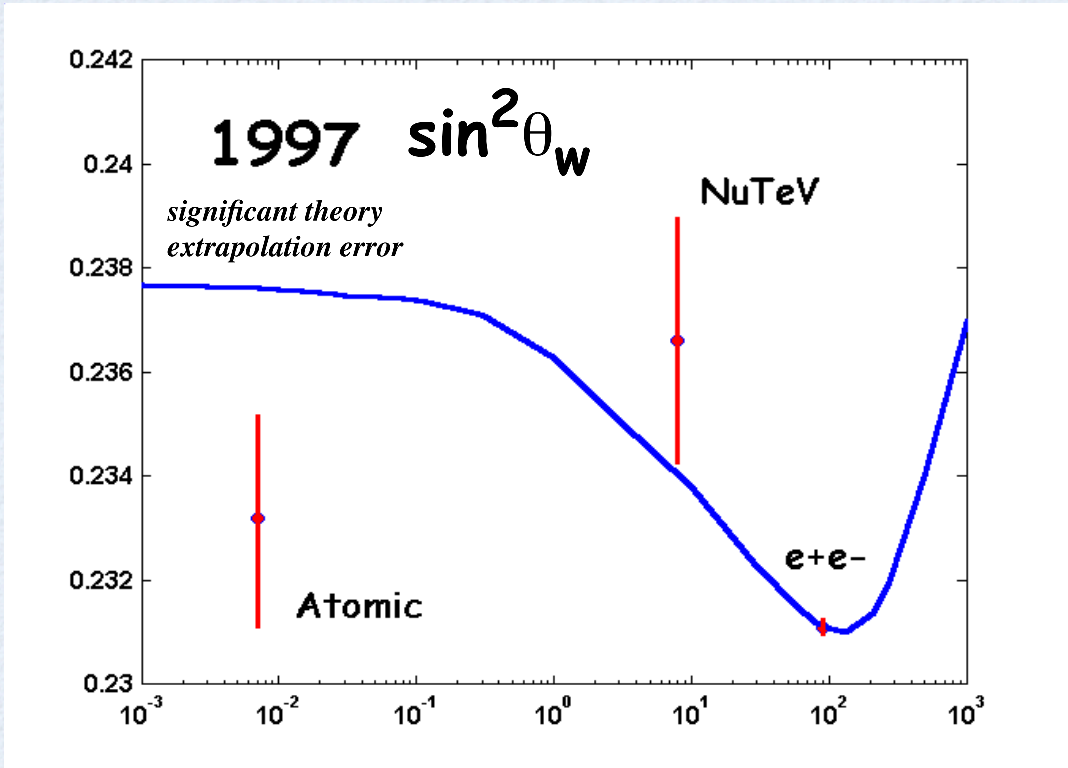

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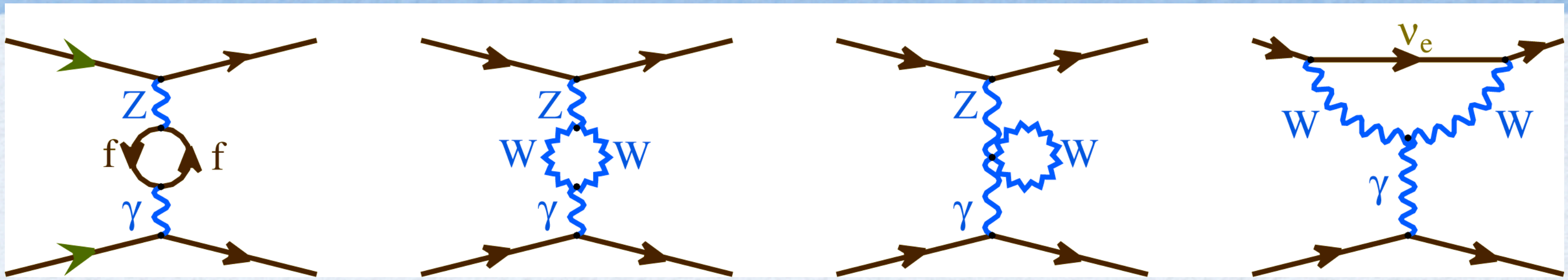

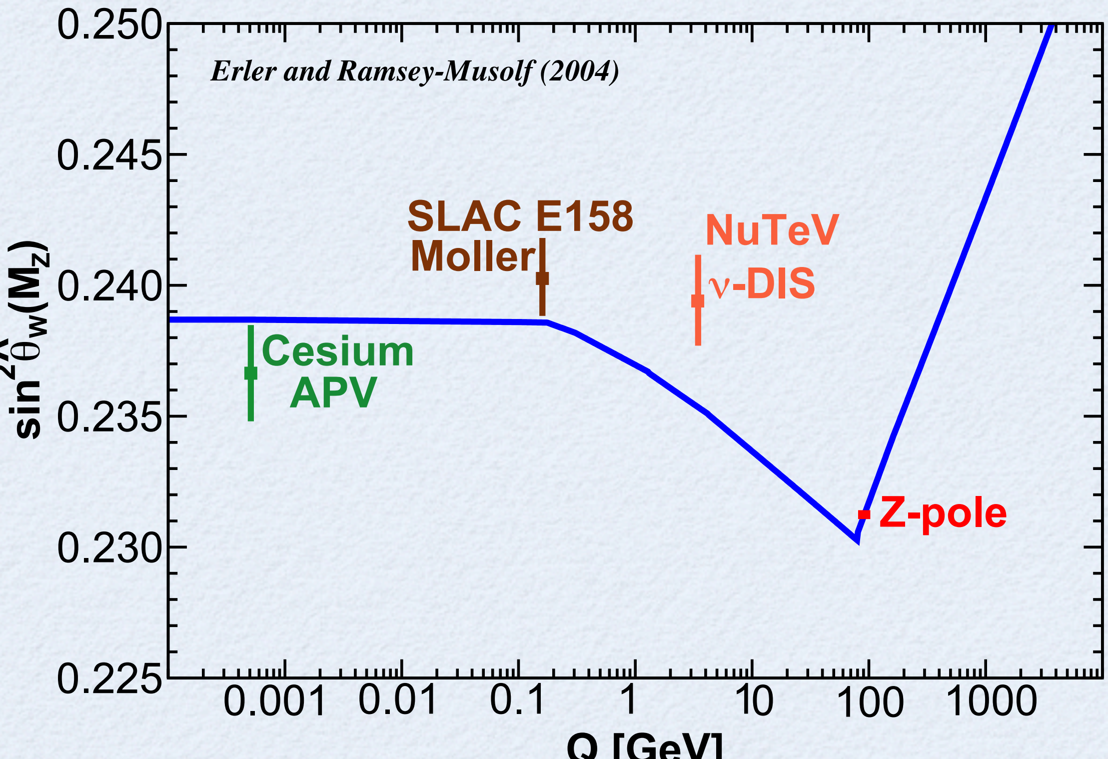

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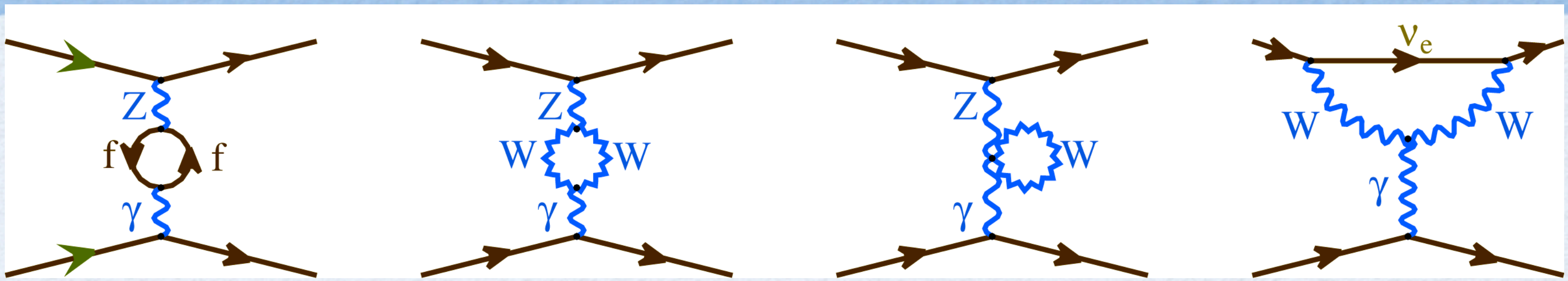

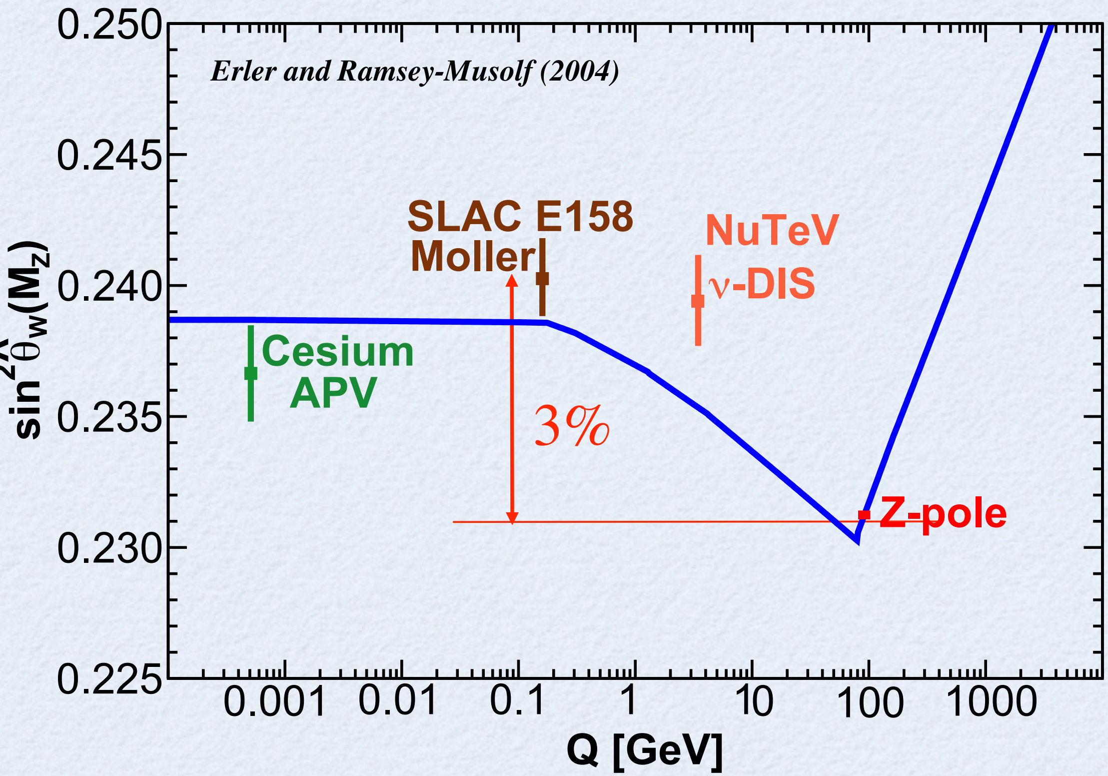

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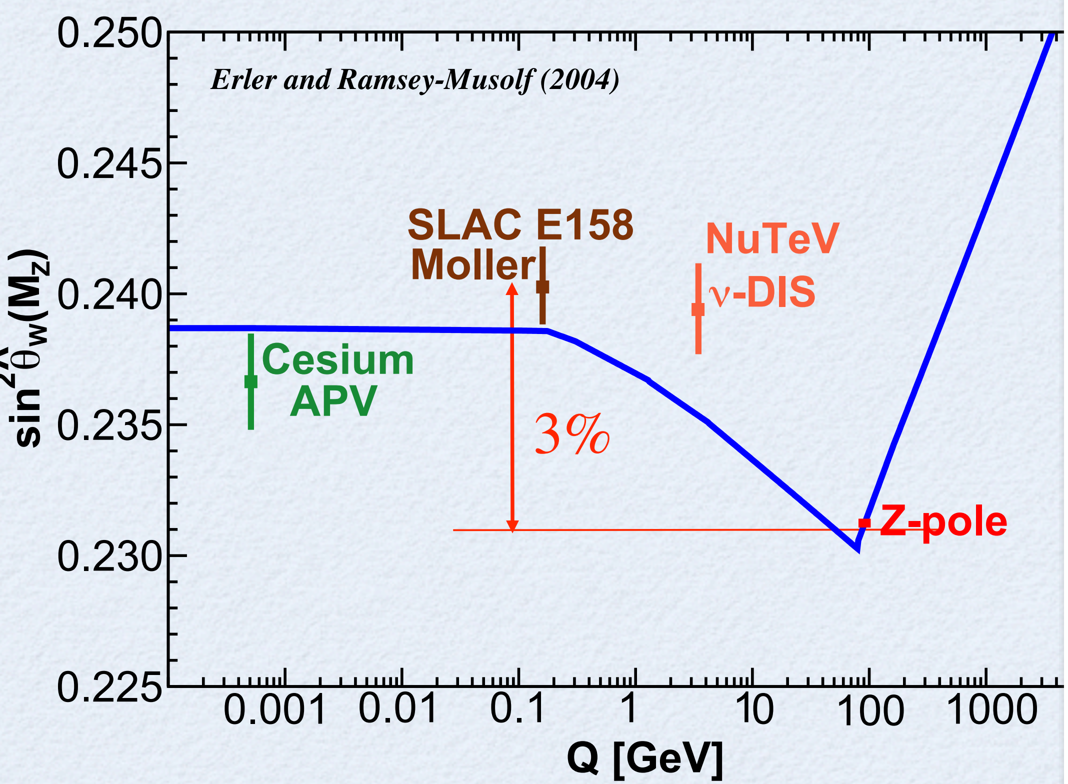
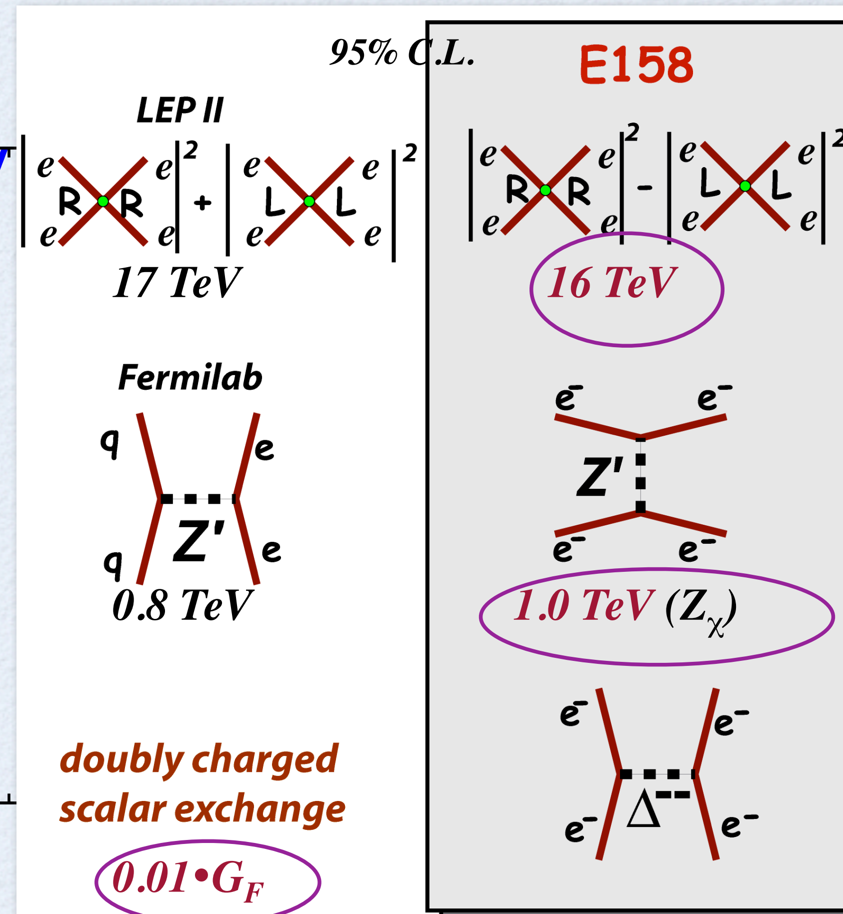
Limits on "New" Physics





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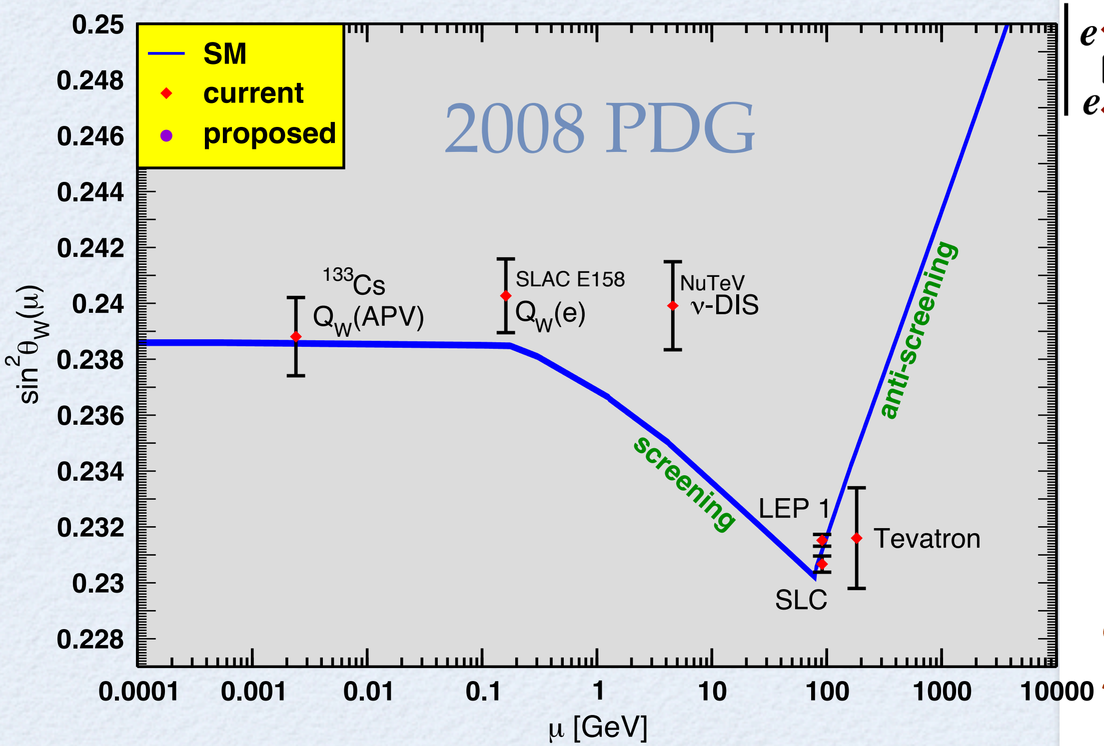
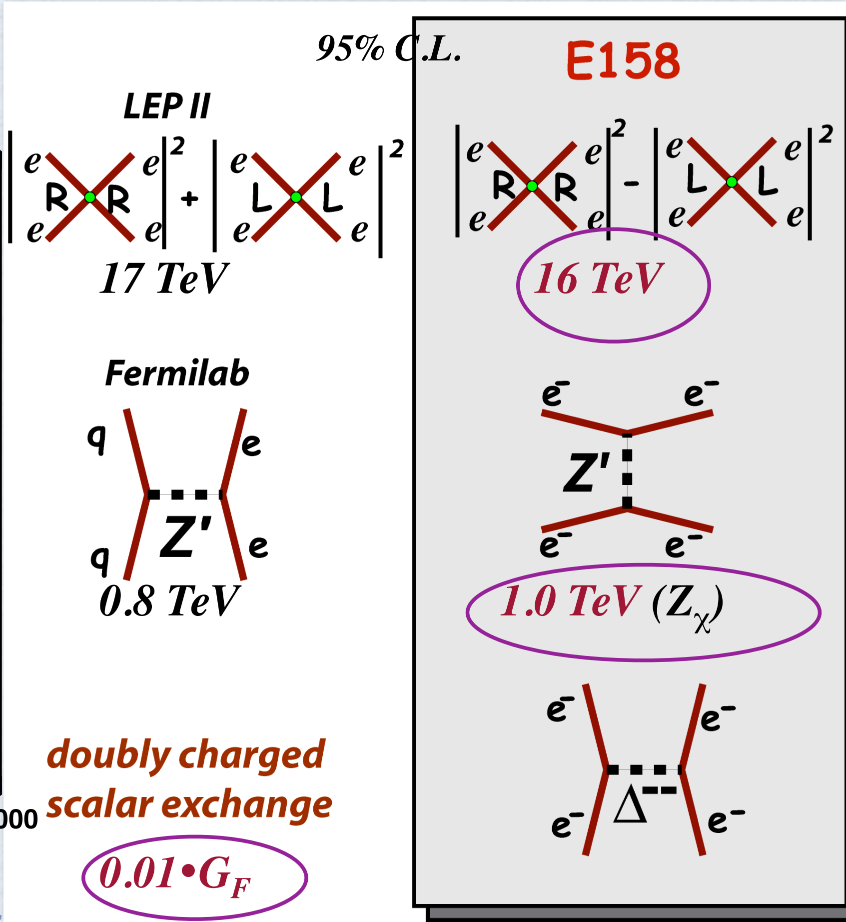
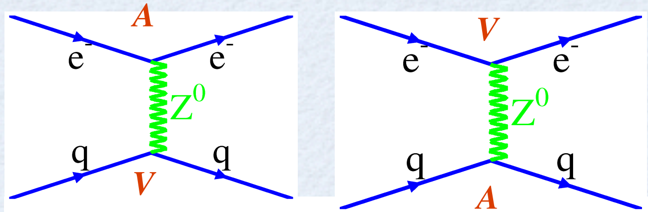


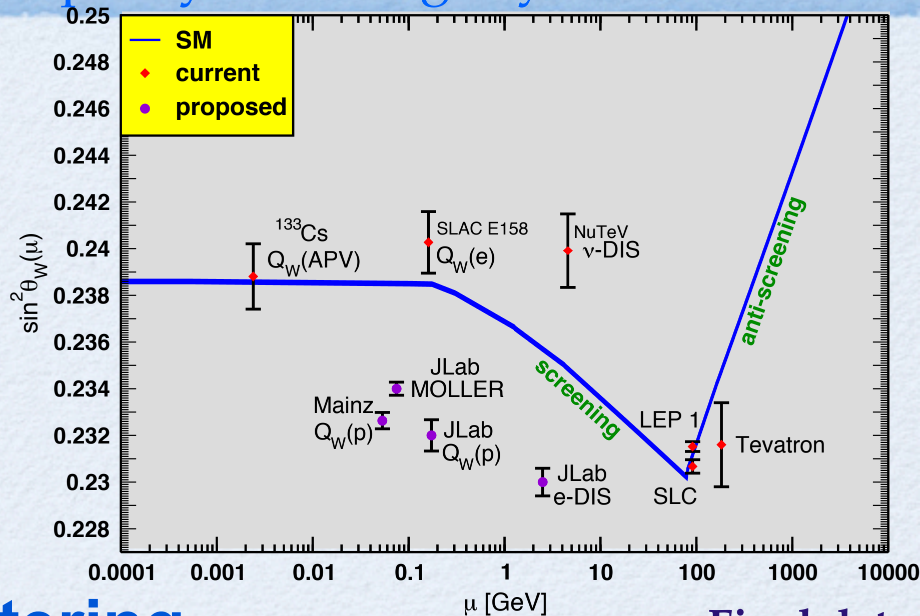


Precision Weak Charges

Current and future measurements of parity-violating asymmetries



$$C_{1i} \equiv 2 g_A^e g_V^i \qquad C_{2i} \equiv 2 g_V^e g_A^i$$



4 e-q couplings and
the e-e coupling

- **Elastic Electron-Proton Scattering**
  - Qweak at JLab has accumulated more than 25% of production data
  - New proposal to improve Qweak by a further factor of 2 at Mainz, Germany
- **Deep Inelastic Scattering off Deuterium**
  - 6 GeV JLab experiment completed: analysis ongoing
  - SoLID: New Apparatus with a large solenoid using 11 GeV beam
- **Møller Scattering**
  - MOLLER: New project to improve E158 by a factor of 5

Final data next year

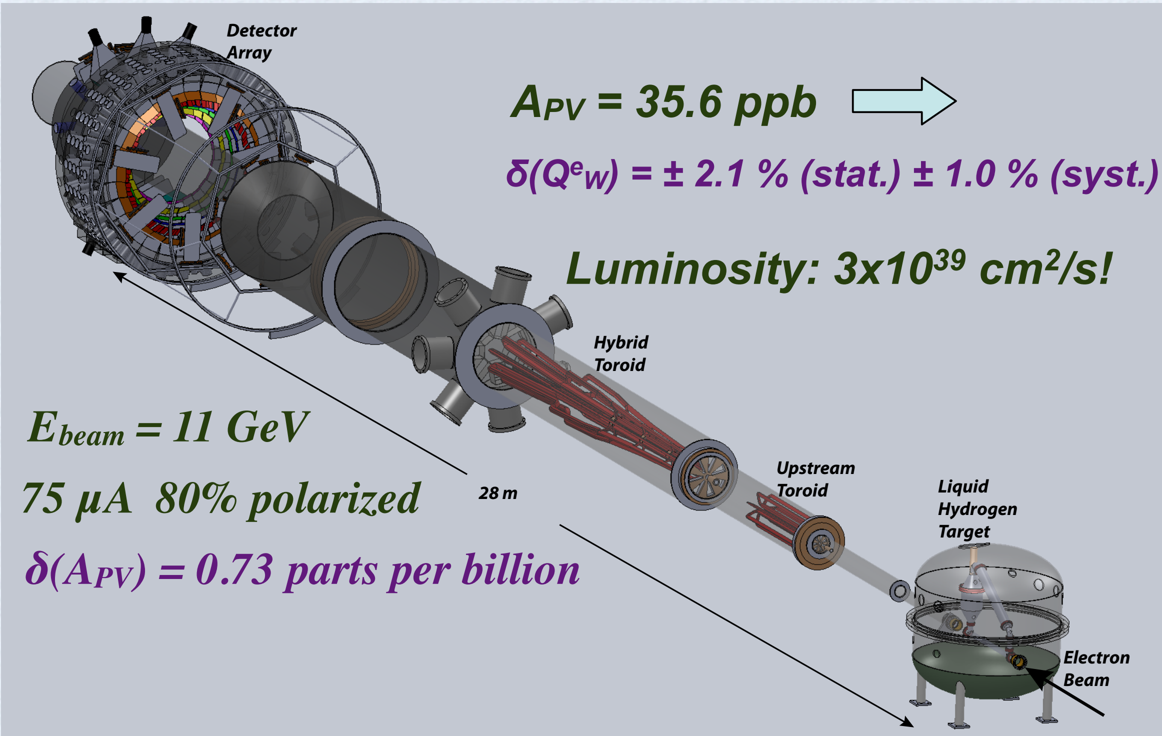
R&D beginning; physics 2015-20

After Jlab energy upgrade in 2013; physics 2015-20

Proposed to run in Hall A after 12 GeV Upgrade

MOLLER at JLab

An ultra-precise measurement of the weak mixing angle using Møller scattering



$$\mathcal{L}_{e_1 e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2} \bar{e}_i \gamma_\mu e_i \bar{e}_j \gamma^\mu e_j \quad \Longrightarrow \quad \frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = 7.5 \text{ TeV}$$

best contact interaction reach for leptons at low OR high energy

To do better for a 4-lepton contact interaction would require:

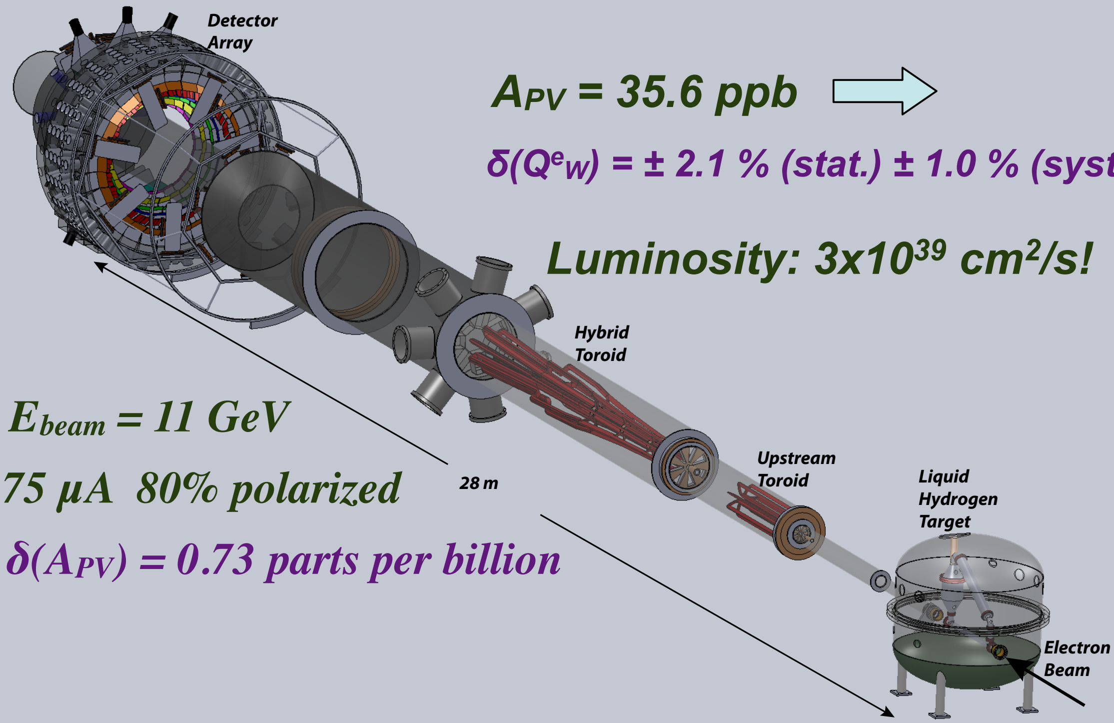
Giga-Z factory, linear collider, neutrino factory or muon collider

Proposed to run in Hall A after 12 GeV Upgrade

MOLLER at JLab

An ultra-precise measurement of the weak mixing angle using Møller scattering

$\delta(\sin^2\theta_W) = \pm\ 0.00026$ (stat.) $\pm\ 0.00012$ (syst.) → ~ 0.1%



A_{PV} = 35.6 ppb →

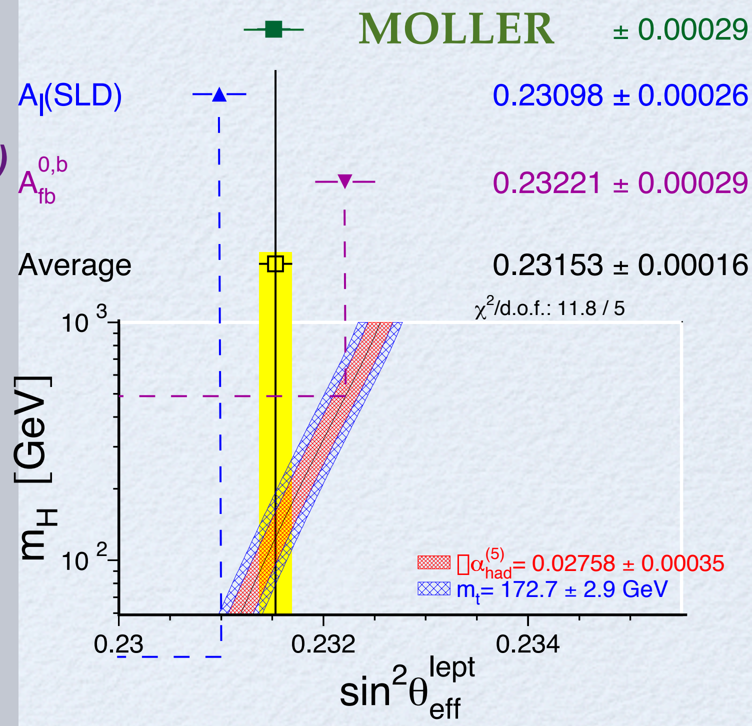
$\delta(Q^e_W) = \pm$ 2.1 % (stat.) $\pm$ 1.0 % (syst.)

Luminosity: $3\mathrm{x}10^{39}$ cm^2/s!

E_{beam} = 11 GeV

75 μA 80% polarized

$\delta(A_{PV})$ = 0.73 parts per billion



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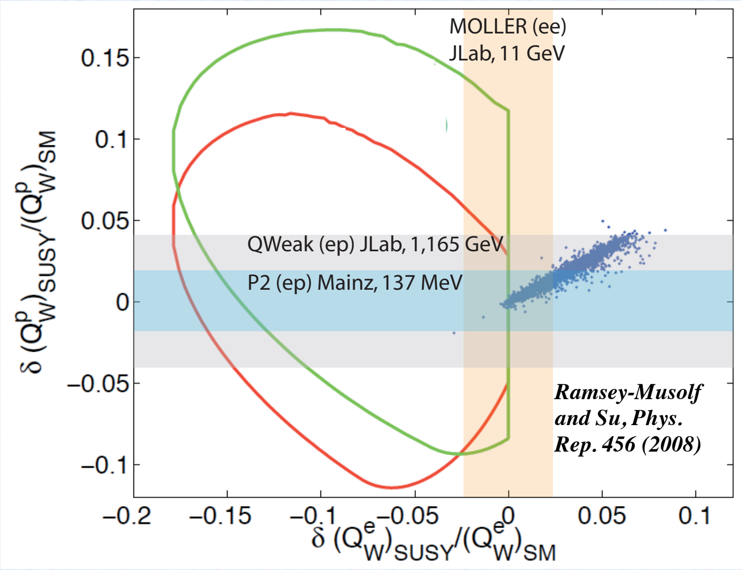
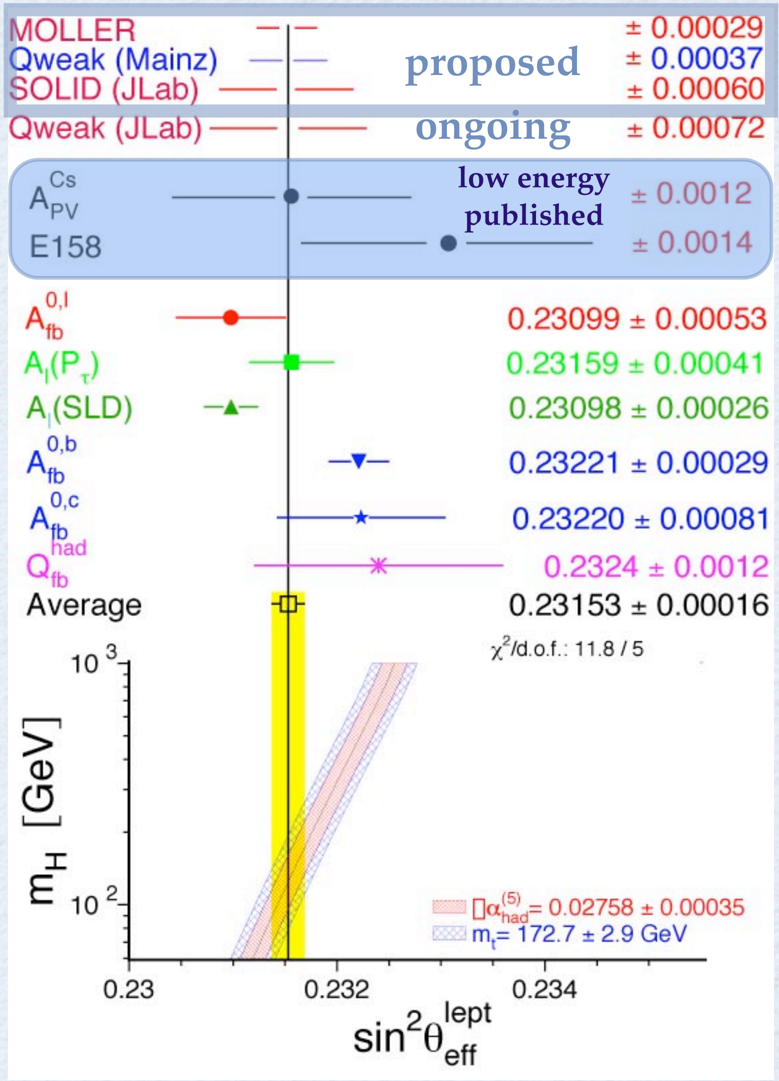
Outlook on Weak Charges

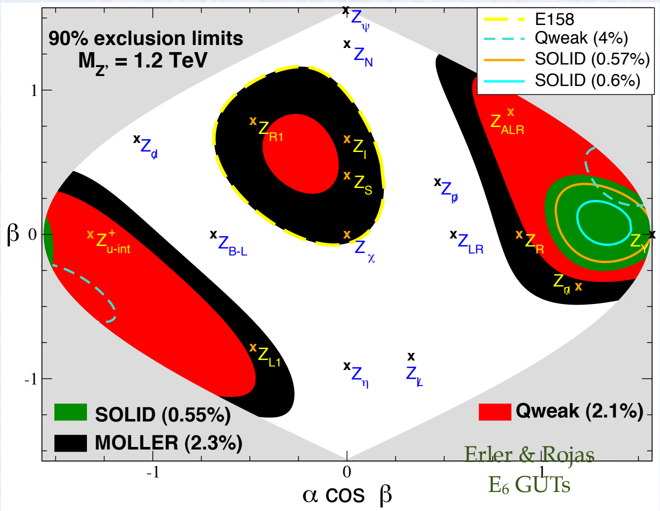
LHC new physics signals could have multiple interpretations: weak charge measurements can discriminate among scenarios

Sensitivity to R-Parity-violating Supersymmetry





Assume a 1.2 TeV resonance observed at LHC which is consistent with being a Z' boson



50's & 60's: Electron Scattering probed nuclear and nucleon substructure

70's: Parity-violating deep inelastic scattering validated the electroweak theory

90's onwards: Physics $\leq$ 1 GeV

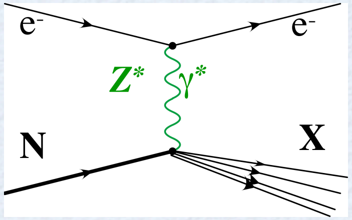
Parity-Violating Electron Scattering & the QCD Structure of the Nucleon

Turn of the century: Physics ~ 1 TeV

Interplay with Physics ~ 1 GeV

PV Deep Inelastic Scattering

With Qweak and APV, C_{1i}'s measured, but C_{2i}'s still unconstrained



A_{PV} in Electron-Nucleon DIS:

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

$Q^2 >> 1\ \mathrm{GeV}^2$, $W^2 >> 4\ \mathrm{GeV}^2$

$$a(x) = \frac{\sum_i C_{1i} Q_i f_i(x)}{\sum_i Q_i^2 f_i(x)} \qquad b(x) = \frac{\sum_i C_{2i} Q_i f_i(x)}{\sum_i Q_i^2 f_i(x)}$$

For ^{2}H, assuming charge symmetry, structure functions largely cancel in the ratio:

$$a(x) = \frac{3}{10}\left[(2C_{1u} - C_{1d})\right] + \cdots \qquad b(x) = \frac{3}{10}\left[(2C_{2u} - C_{2d})\frac{u_v(x) + d_v(x)}{u(x) + d(x)}\right] + \cdots$$

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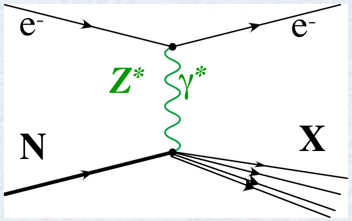

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Must measure A_{PV} to 0.5% fractional accuracy!

Feasible at 6 GeV at Jlab ⇨ ***luminosity > 10^{38}/cm^2/s***

well-suited for 11 GeV after the upgrade

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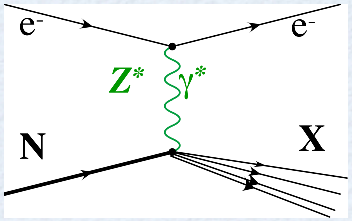

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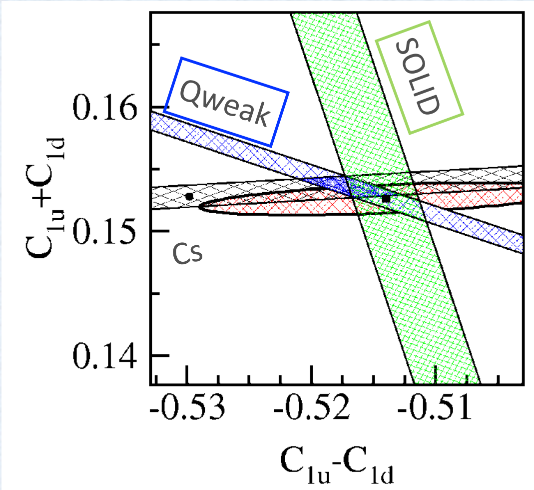
well-suited for 11 GeV after the upgrade

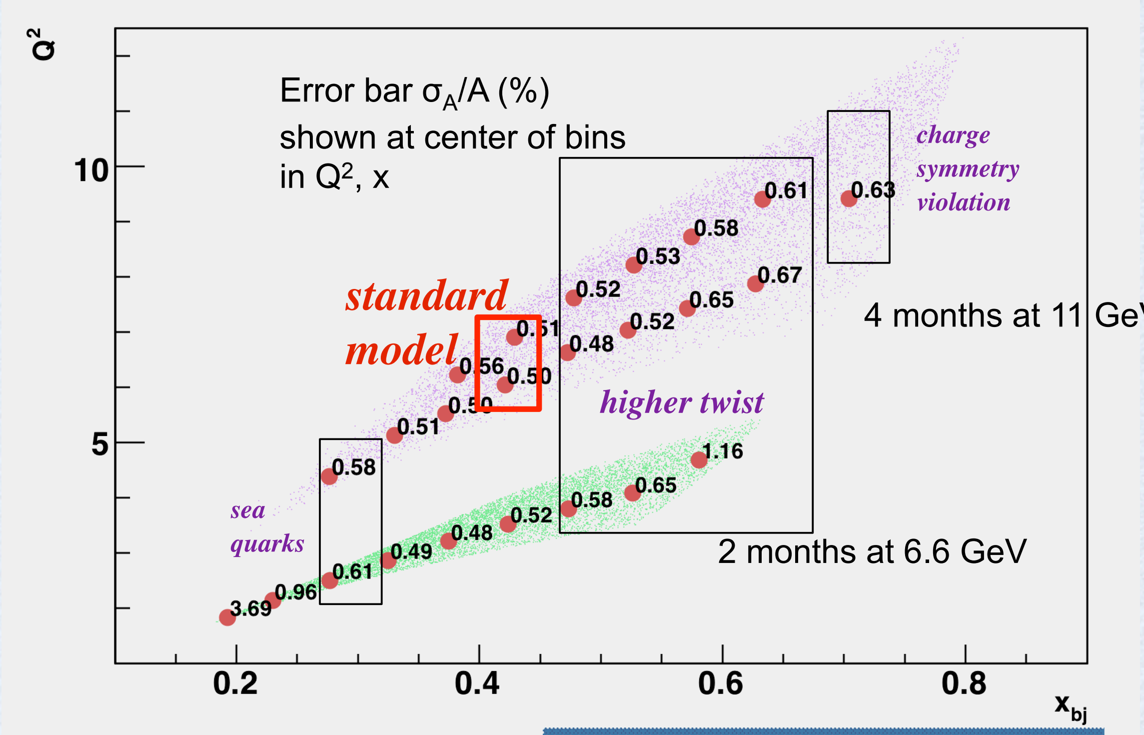
- First experiment at 6 GeV: ran Oct-Dec '09; ~4% accuracy @ Q^2 ~ 1-2 GeV^2
- Approved Hall C proposal at 11 GeV using planned upgrade for spectrometers
- SOLID: New large acceptance solenoidal spectrometer approved for Hall A

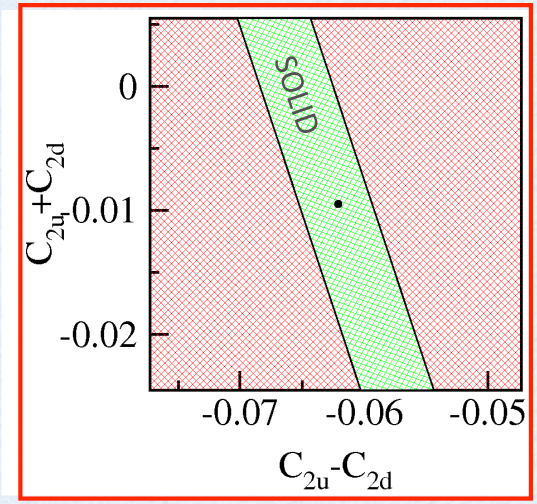
Proposed to run in Hall A after 12 GeV Upgrade

SOLID at Jefferson Laboratory

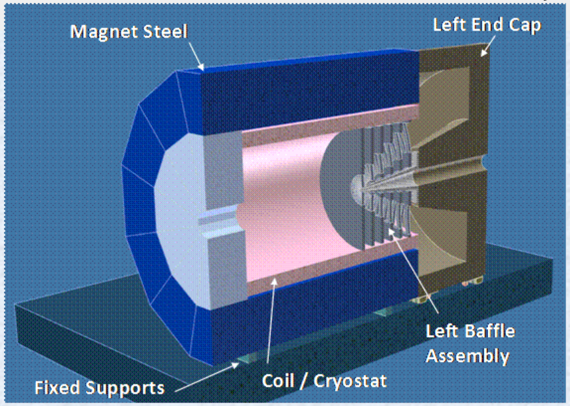
Simultaneous measurements of ~ 20 “NuTeV” points







Strategy: **sub-1% precision** over broad kinematic range for **sensitive Standard Model test** *and* **detailed study of hadronic structure effects**



Electroweak Physics at an EIC

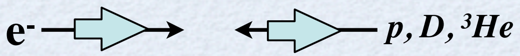
luminosity large: precision measurements of PV observables

$$\frac{1}{2m_N} W^i_{\mu\nu} = -\frac{g_{\mu\nu}}{m_N} F^i_1 + \frac{p_\mu p_\nu}{m_N(p\cdot q)} F^i_2 + i\frac{\epsilon_{\mu\nu\alpha\beta}}{2(p\cdot q)}\left[\frac{p^\alpha q^\beta}{m_N} F^i_3 + 2q^\alpha S^\beta g^i_1 - 4xp^\alpha S^\beta g^i_2\right] - \frac{p_\mu S_\nu + S_\mu p_\nu}{2(p\cdot q)} g^i_3 + \frac{S\cdot q}{(p\cdot q)^2} p_\mu p_\nu g^i_4 + \frac{S\cdot q}{p\cdot q} g_{\mu\nu} g^i_5$$

Ji, Vogelsang, Blümlein, ...
Anselmino, Efremov & Leader, Phys. Rep. **261** (1995)

Machine configurations: GeV & fb^{-1}

- **11 x 60: 100 going to 500**
- **5 x 250: 70 going to 350**
- **11 x 250: 100 going to 500**
- **20 x 325: 100 going to 500**



***polarized* electron, *unpolarized* hadron**

$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A \frac{F_1^{\gamma Z}}{F_1^\gamma} + g_V \frac{f(y)}{2}\frac{F_3^{\gamma Z}}{F_1^\gamma}\right]$$

***unpolarized* electron, *polarized* hadron**

$$A_{TPV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_V \frac{g_5^{\gamma Z}}{F_1^\gamma} + g_A f(y)\frac{g_1^{\gamma Z}}{F_1^\gamma}\right]$$

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e^- → ← *p, D, ^{3}He*

polarized electron, unpolarized hadron

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proton

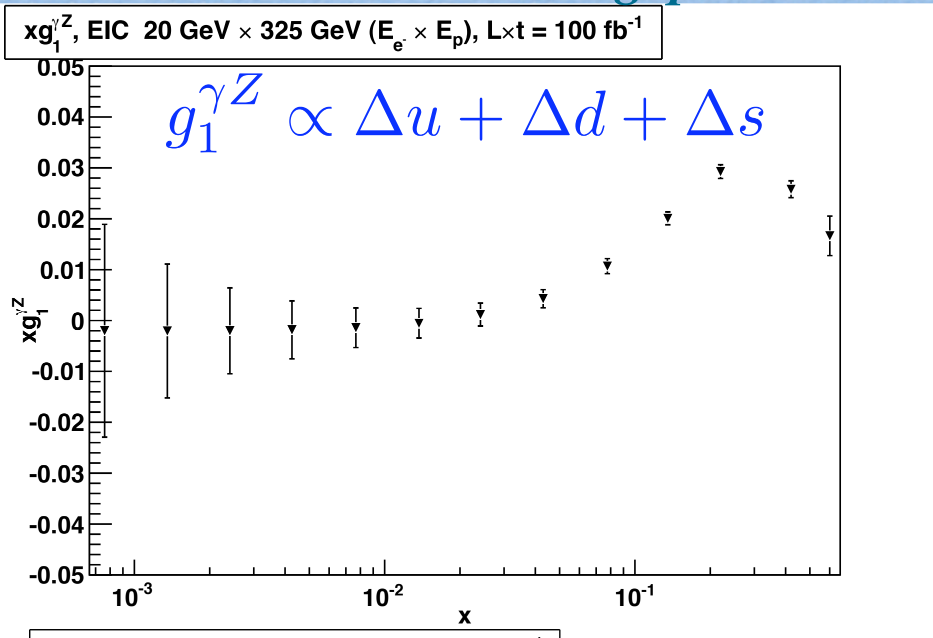
$$F_1^{\gamma Z} \propto u + d + s$$
$$F_3^{\gamma Z} \propto 2u_v + d_v$$
$$g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s$$
$$g_5^{\gamma Z} \propto 2\Delta u_v + \Delta d_v$$

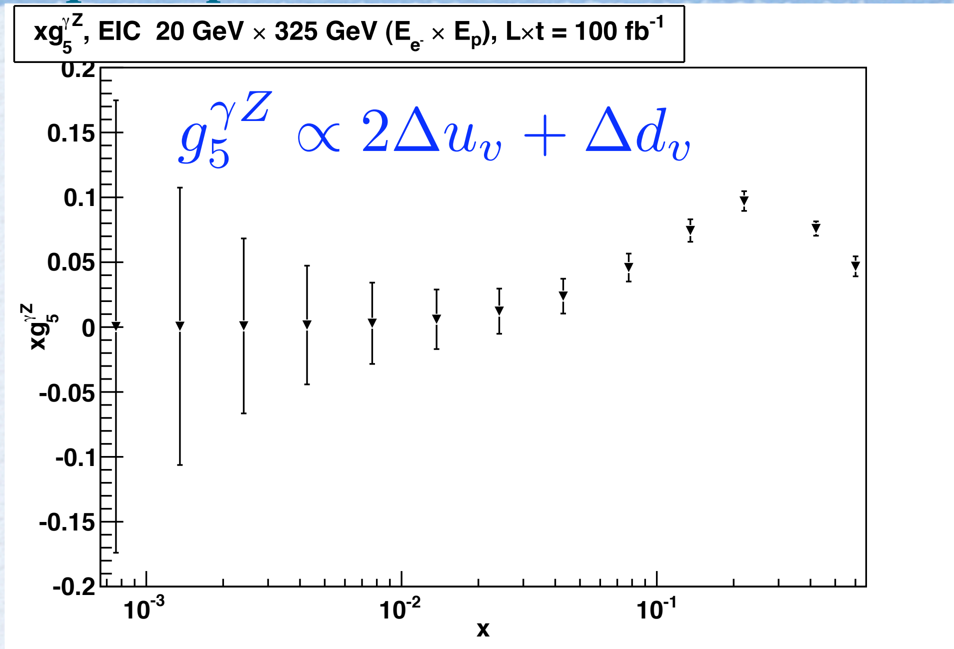
deuteron

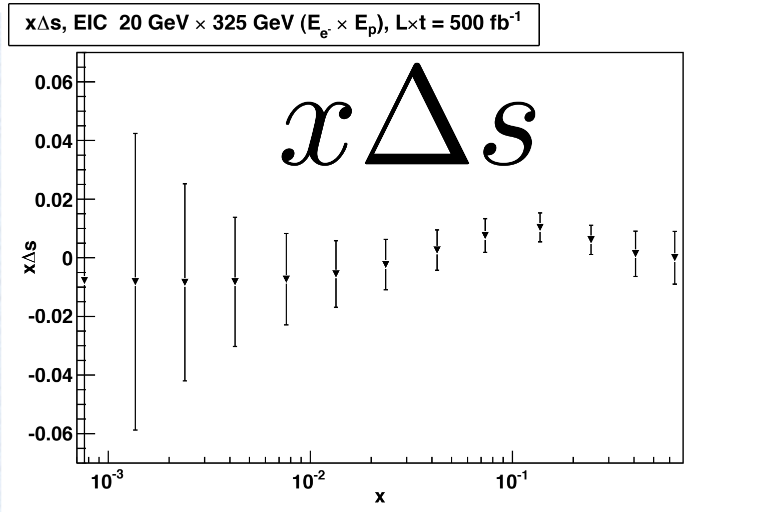
$$F_1^{\gamma Z} \propto u + d + 2s$$
$$F_3^{\gamma Z} \propto u_v + d_v$$
$$g_1^{\gamma Z} \propto \Delta u + \Delta d + \Delta s$$
$$g_5^{\gamma Z} \propto \Delta u_v + \Delta d_v$$

Help 6-Flavor Separation

Including quark and anti-quark polarizations







A cross-check showing unambiguously non-zero delta-s in an inclusive measurement?

Semi-inclusive measurements lose statistical power at x ~ 0.1, and have significant theoretical interpretation issues

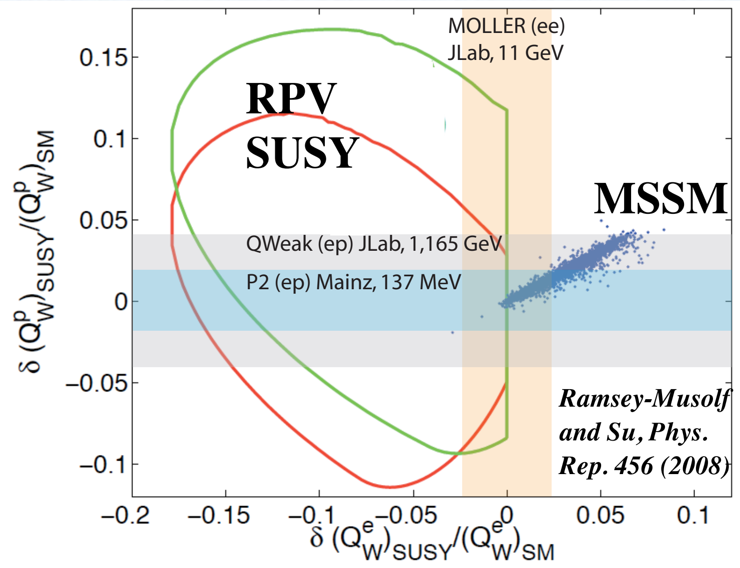
Summary

- **Parity-violating electron scattering has played a major in the development and tests of electroweak interactions over the past 3 decades**
- **The 2-decade search for strange form factors nearly complete: sensitive probe of low energy QCD dynamics**
    - New result from HappexIII just submitted to PRL
- **The physics results and the technical progress have set the stage for the next era of ultra-precise measurements:**
    - TeV-scale electroweak physics beyond the Standard Model
    - Neutron skin of a heavy nucleus
        - first result on ^{208}Pb shows neutron radius is bigger; followup precision measurements planned
    - QCD structure of the nucleon
- **A high-luminosity electron-ion collider offers the possibility to measure entirely new structure functions using parity-violating observables**

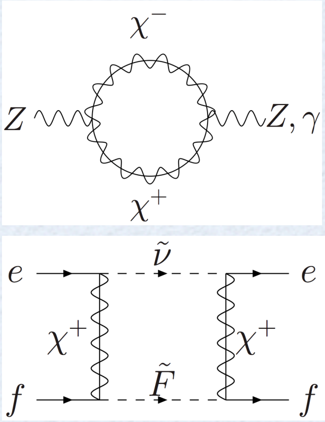
Backups

MOLLER Physics Reach

Assume either SUSY or Z′ discovered at LHC



MSSM sensitivity if light super-partners, large tanβ



Does Supersymmetry provide a candidate for dark matter?

- B and/or L need not be conserved: neutralino decay
- Depending on size and sign of deviation: loses appeal as a dark matter candidate

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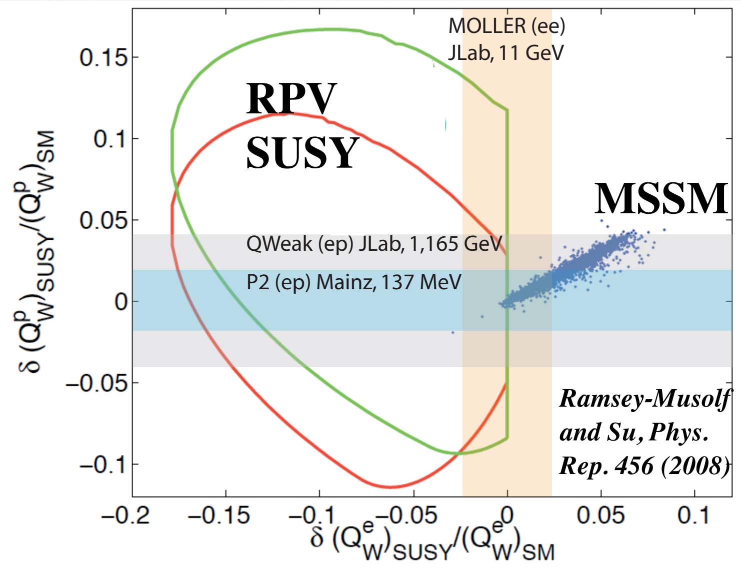

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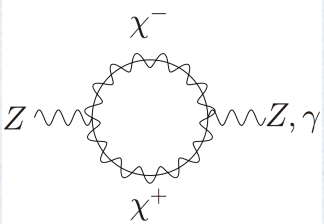

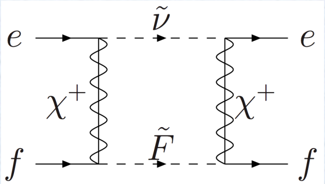

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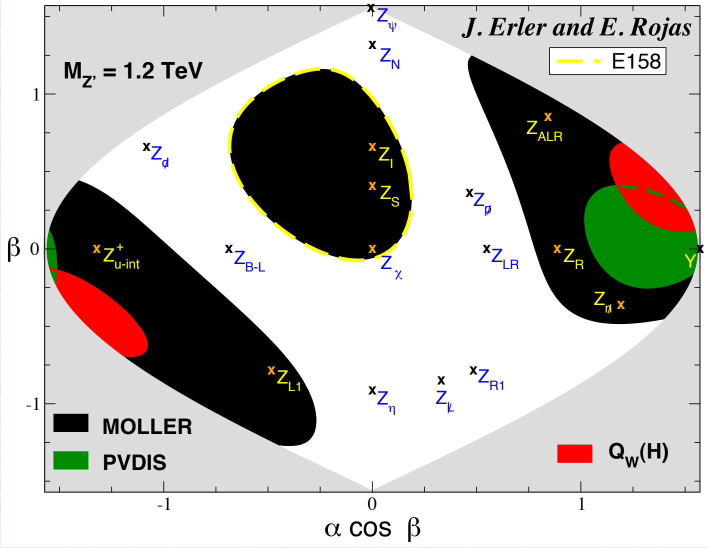
- Depending on size and sign of deviation: loses appeal as a dark matter candidate

- *Virtually all GUT models predict new Z's*
- *LHC reach ~ 5 TeV, but....*
- *For 'light' 1-2 TeV, Z' properties can be extracted*

Suppose a 1 to 2 TeV heavy Z'
is discovered at the LHC

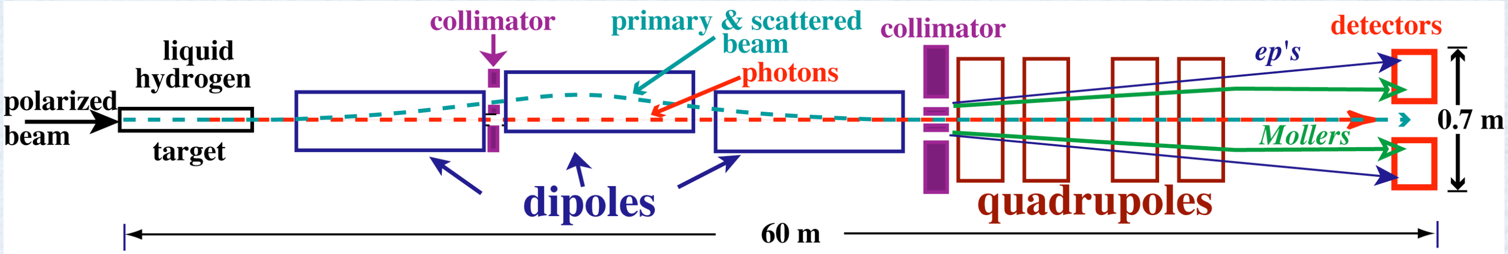
- **Can we point to an underlying GUT model?**



~ 1999: electron-electron weak attractive force had never been measured!

SLAC E158 Proposal

~ 10 ppb statistical error at highest E_{beam}, ~ 0.4% error on weak mixing angle



A large number of technical challenges

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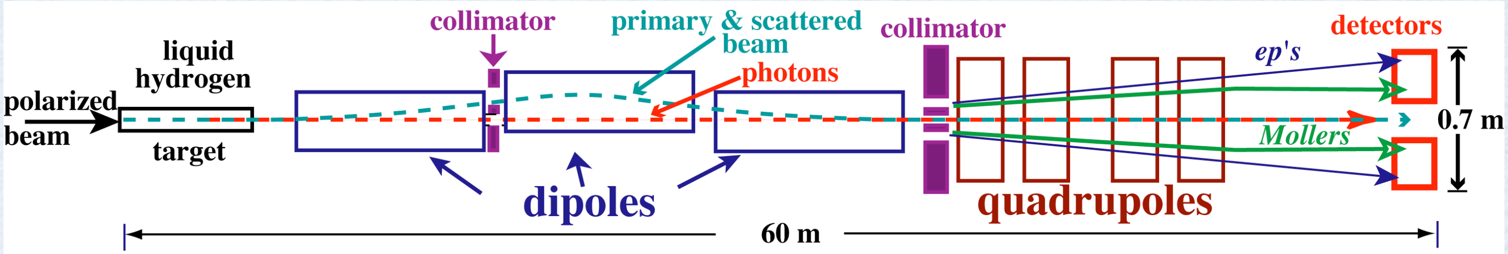
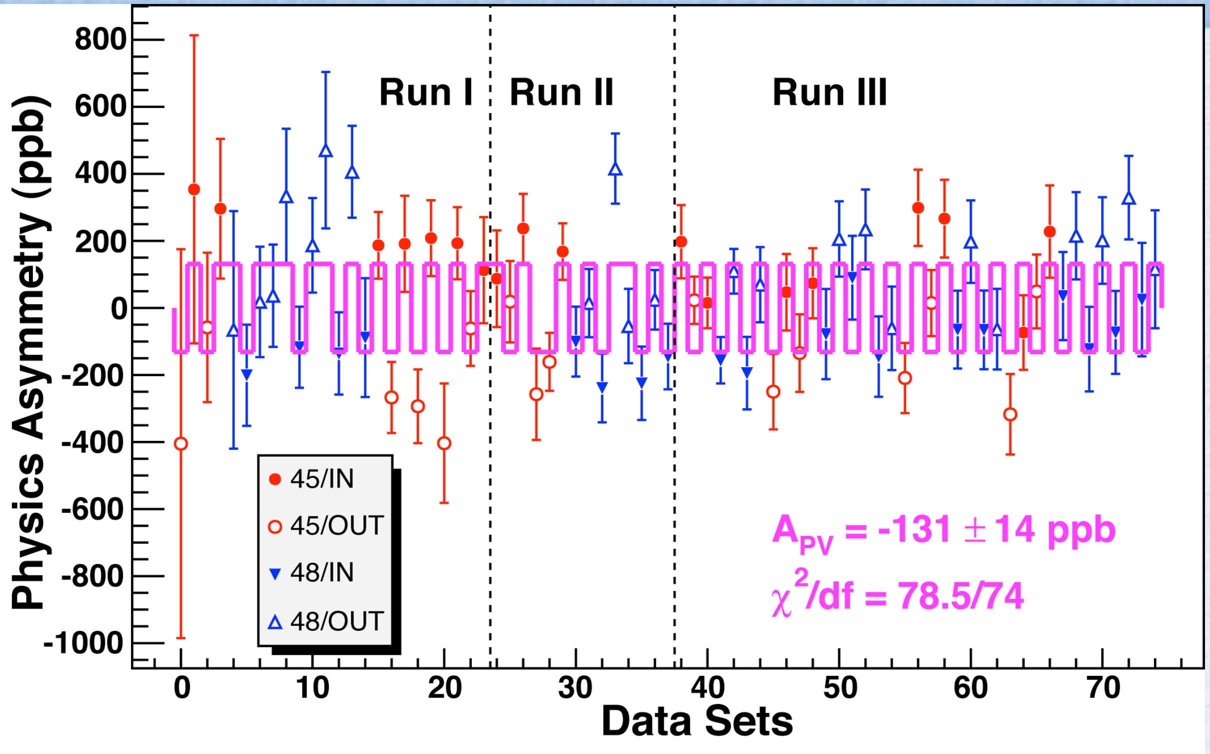


A large number of technical challenges

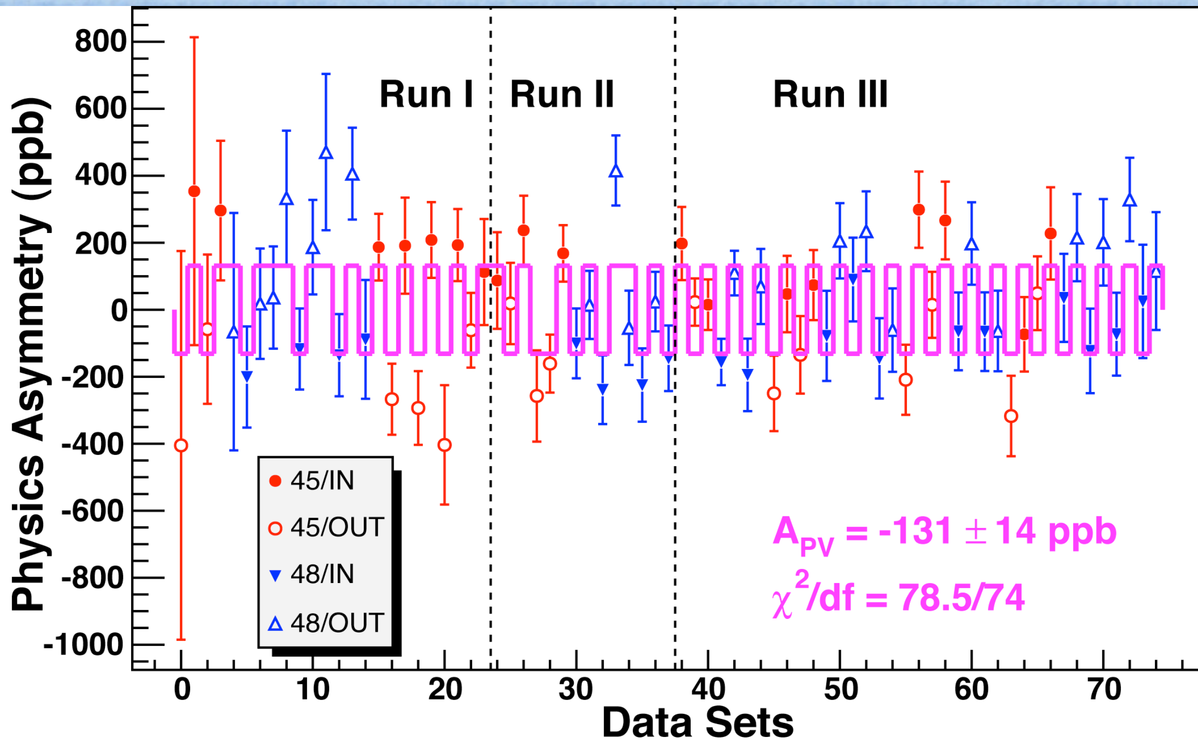
- 10 nm control of beam centroid on target
  - R&D on polarized source laser transport elements
- 12 microamp beam current maximum
  - 1.5 meter Liquid Hydrogen target
- 20 Million electrons per pulse @ 120 Hz
  - 200 ppm pulse-to-pulse statistical fluctuations
    - *Electronic noise and density fluctuations < 10^{-4}*
    - *Pulse-to-pulse monitoring resolution ~ 1 micron*
    - *Pulse-to-pulse beam fluctuations < 100 microns*
  - 100 Mrad radiation dose from scattered flux
    - *State-of-the-art radiation-hard integrating calorimeter*
- Full Azimuthal acceptance with θ_{lab} ~ 5 mrad
  - Quadrupole spectrometer
  - Complex collimation and radiation shielding issues

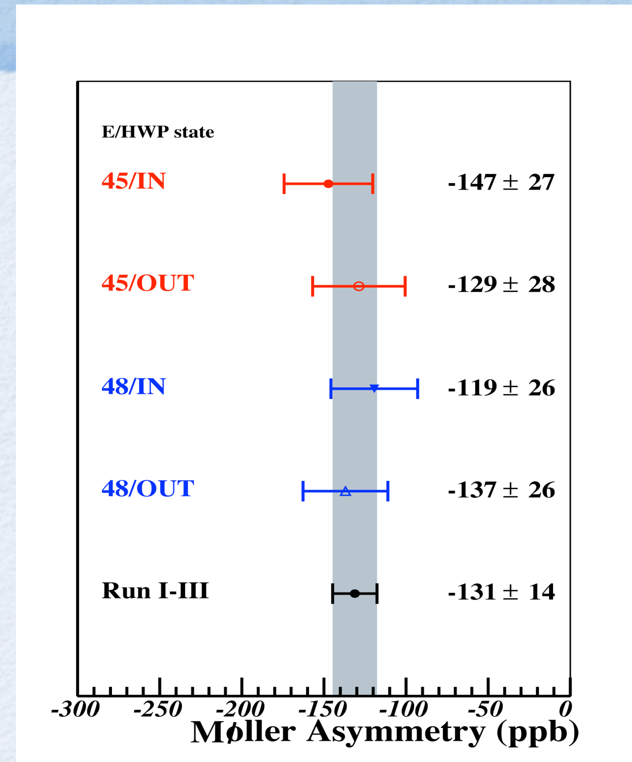
SLAC E158 Data

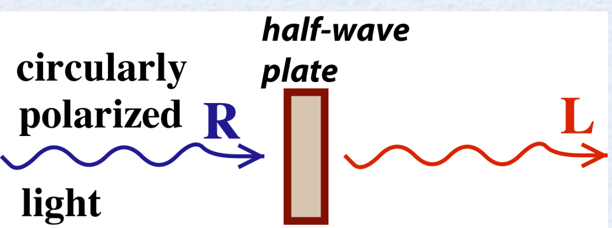


Phys. Rev. Lett. **95** 081601 (2005)

SLAC E158 Data



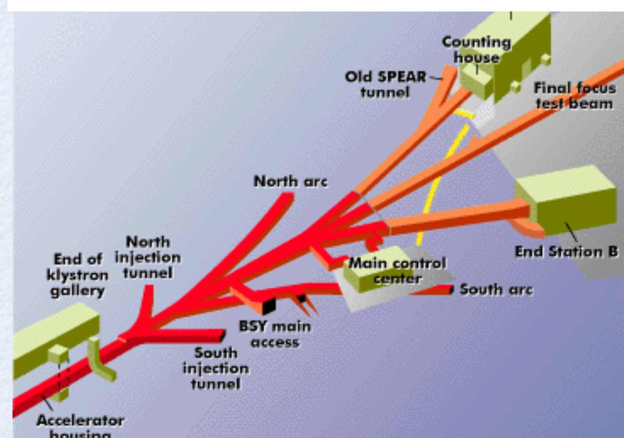




g-2 spin precession

45 GeV: 14.0 revs

48 GeV: 14.5 revs



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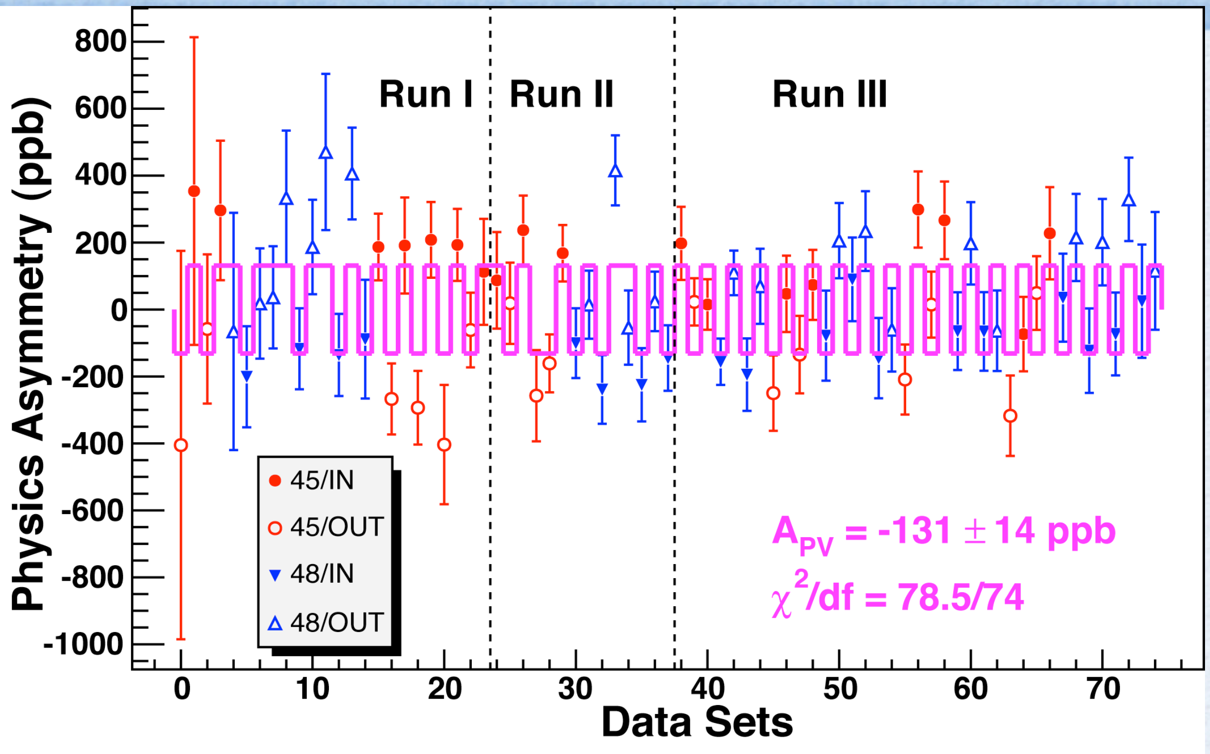

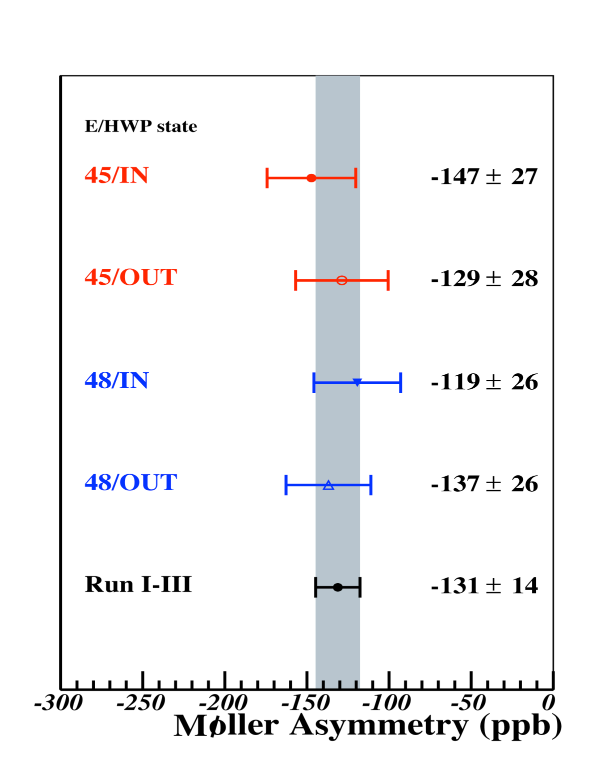

$A_{PV} = (-131 \pm 14 \pm 10) \times 10^{-9}$

$$A_{PV} \approx -1 \times 10^{-7} \times E_{beam} \times P_{beam} \times (1 - 4\sin^2\vartheta_W)$$

$$\approx 250\,ppb$$ *Phys. Rev. Lett.* **95** 081601 (2005)

MOLLER Status

Proposal submitted to Nuclear Physics Division of the Department of Energy

sub-system	Institutions
polarized source	*UVa, JLab, Miss. St.*
Target	*JLab, VaTech, Miss. St.*
Spectrometer	*Canada, ANL, MIT, UVa*
Integrating Detectors	*Syracuse, Canada, JLab*
Luminosity Monitors	*VaTech, Ohio U.*
Pion Detectors	*UMass/Smith, LATech*
Tracking Detectors	*William & Mary, Canada, INFN Roma*
Electronics	*Canada, JLab*
Beam Monitoring	*UMass, JLab*
Polarimetry	*UVa, Syracuse, JLab, CMU, ANL, Miss. St., Claremont-Ferrand, Mainz*
Data Acquisition	*Ohio U., Rutgers U.*
Simulations	*LATech, UMass/Smith, UC Berkeley*

- Strong Collaboration being formed
  - ~ 100 authors, ~ 30 institutions
  - Expertise: A4, HAPPEX, PREX, Qweak, E158
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- Recent Progress
  - Director's review chaired by C. Prescott: strong endorsement and encouragement to proceed
  - Developed a conceptual design of spectrometer, and a cost range (~ 20M$)
- Funding
  - Recently submitted a proposal to DoE Nuclear Physics with a request to enter the CD-n process
  - collaboration committed to construction project
- Potential Schedule
  - goal is for funding to begin early 2014
  - goal is for installation in 2016
- Possible Beam Time Allocation
  - Run I: 3 months (6 wks setup + 6 wks data): E158 error
  - Run II: 6 months: 25% statistics; already world's best measurement
  - Run III: 2 years: full statistics with 60% efficiency

Signal & Backgrounds

parameter	value
cross-section	*45.1 μBarn*
Rate @ 75 μA	*135 GHz*
pair stat. width (1 kHz)	*82.9 ppm*
$\delta(A_{raw})$ *(6448 hrs)*	*0.544 ppb*
$\delta(A_{stat})/A$ *(80% pol.)*	*2.1%*
$\delta(\sin^2\theta_W)_{stat}$	*0.00026*

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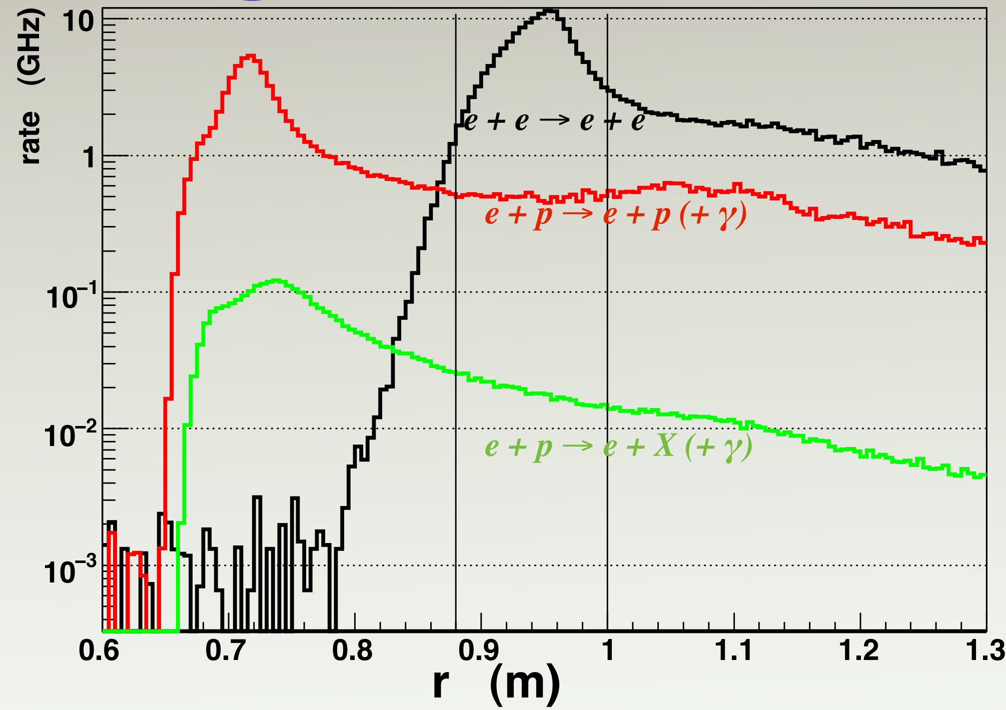

- Elastic e–p scattering
  - well-understood and testable with data
  - 8% dilution, 7.5±0.4% correction
- Inelastic e–p scattering
  - sub-1% dilution
  - large EW coupling, 4±0.4% correction
  - variation of A_{PV} with r and ϕ

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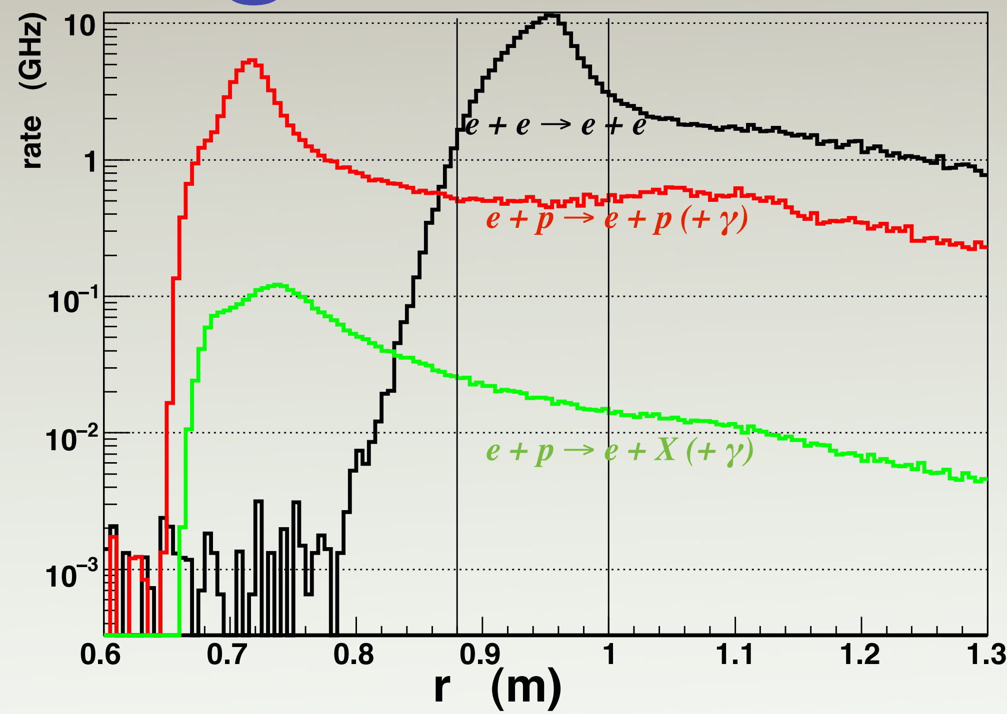

- photons and neutrons
  - mostly 2-bounce collimation system
  - dedicated runs to measure “blinded” response
- pions and muons
  - real and virtual photo-production and DIS
  - prepare for continuous parasitic measurement
  - estimate 0.5 ppm asymmetry @ 0.1% dilution
- Elastic e-p scattering
  - well-understood and testable with data
  - 8% dilution, 7.5±0.4% correction
- Inelastic e-p scattering
  - sub-1% dilution
  - large EW coupling, 4±0.4% correction
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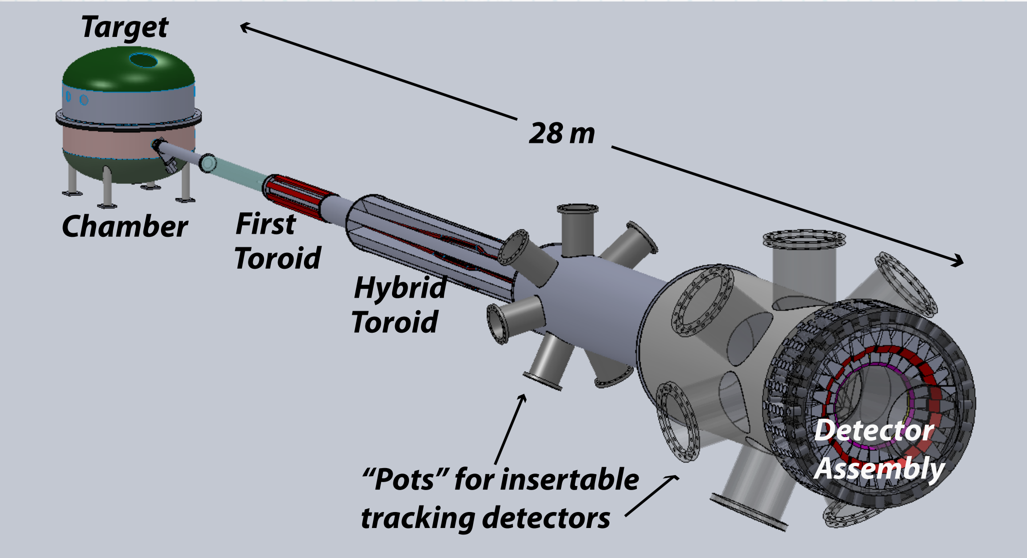
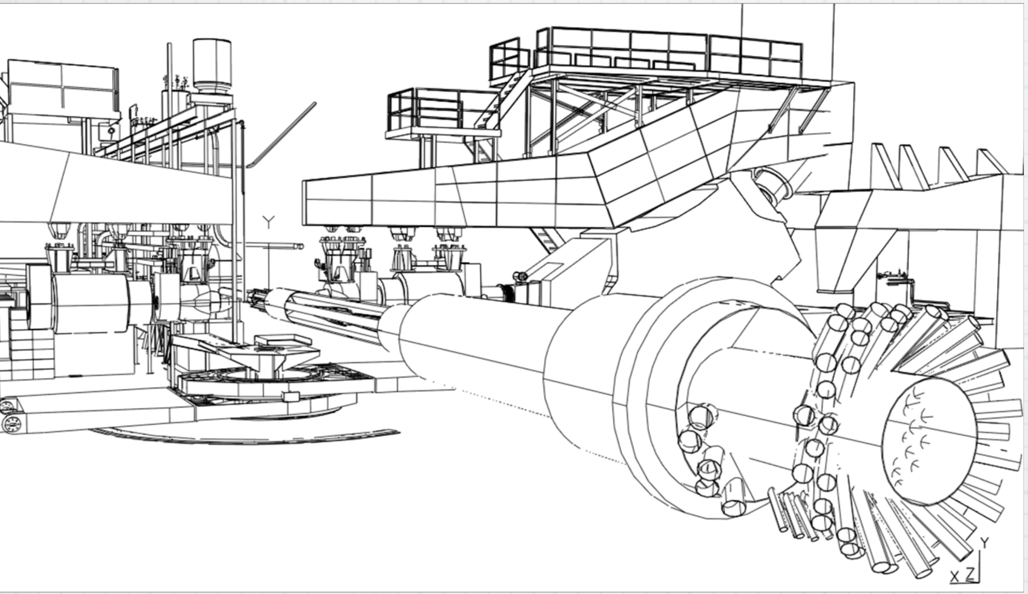
MOLLER Apparatus





* Polarized Beam

- Unprecedented polarized luminosity
- unprecedented beam stability

* Liquid Hydrogen Target

- 5 kW dissipated power (2 X Qweak)
- computational fluid dynamics

* Toroidal Spectrometer

- Novel 7 "hybrid coil" design
- warm magnets, aggressive cooling

* Integrating Detectors

- build on Qweak and PREX
- intricate support & shielding
- radiation hardness and low noise

compact structure: plan to make apparatus and sheilding easily removable

Statistics & Systematics

parameter	MOLLER	E158	Qweak
Rate	*135 GHz*	*3 GHz*	*6 GHz*
pair stat. width	*82.9 ppm*	*200 ppm*	*400 ppm*
$\delta(A_{raw})$	*0.544 ppb*	*11 ppb*	*4 ppb*
$\delta(A_{stat})/A$	*2.1%*	*10%*	*3%*
$\delta(\sin^2\theta_W)_{stat}$	*0.00026*	*0.001*	*0.0007*

Accuracy goals are factors of 2 to 10 beyond those of E158 & Qweak

Irreducible Backgrounds:

- **Elastic e-p scattering**
  - well-understood and testable with data
  - 8% dilution, 7.5±0.4% correction
- **Inelastic e-p scattering**
  - sub-1% dilution
  - large EW coupling, 4±0.4% correction
  - variation of A_{PV} with r and ϕ

source of error	% error
absolute value of Q^2	*0.5*
beam second order	*0.4*
longitudinal beam polarization	*0.4*
inelastic e-p scattering	*0.4*
elastic e-p scattering	*0.3*
beam first order	*0.3*
pions and muons	*0.3*
transverse polarization	*0.2*
photons and neutrons	*0.1*
Total	1.0

Technical Challenges

- ~ 150 GHz scattered electron rate
  - Design to flip Pockels cell ~ 2 kHz
  - 80 ppm pulse-to-pulse statistical fluctuations
    - *Electronic noise and density fluctuations < 10^{-5}*
    - *Pulse-to-pulse beam jitter ~ 10s of microns at 1 kHz*
    - *Pulse-to-pulse beam monitoring resolution ~ 10 ppm and few microns at 1 kHz*
- 1 nm control of beam centroid on target
  - Modest improvementin polarized source laser controls
  - Improved methods of "slow helicity reversal"
- > 10 gm/cm^2 target needed
  - 1.5 m Liquid Hydrogen target: ~ 5 kW @ 85 μA
- Full Azimuthal acceptance with θ_{lab} ~ 5 mrad
  - novel two-toroid spectrometer
  - radiation hard, highly segmented integrating detectors
- Robust and Redundant 0.4% beam polarimetry
  - Plan to pursue both Compton and Atomic Hydrogen techniques

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- One dedicated postdoc focused on spectrometer (thanks!)
- Engineering advice is "pro-bono" right now

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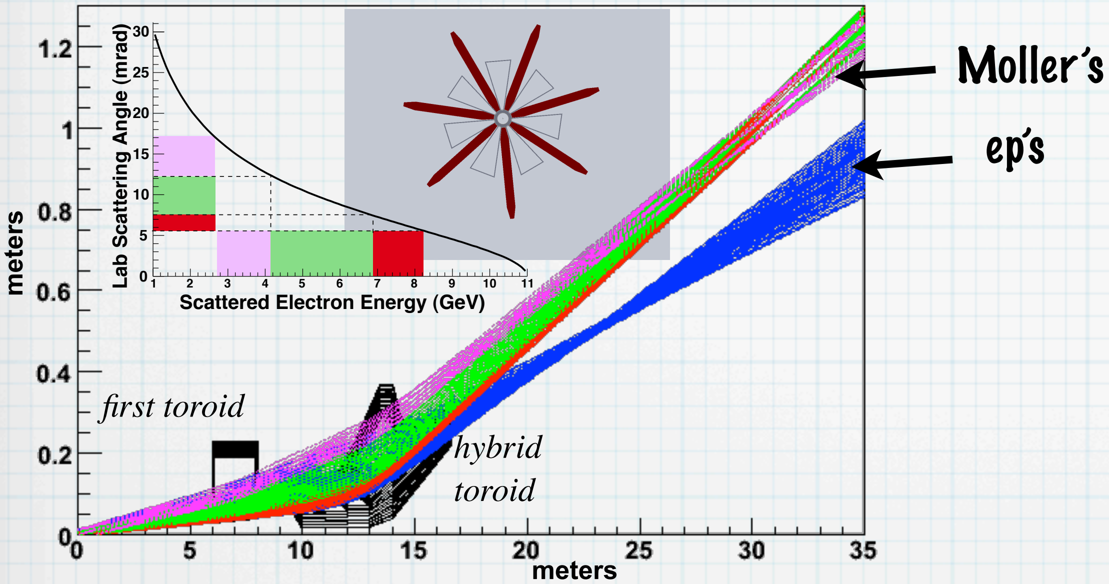
Collaboration is preparing a prioritized R&D plan, but the spectrometer is at the top of the list

Spectrometer Concept



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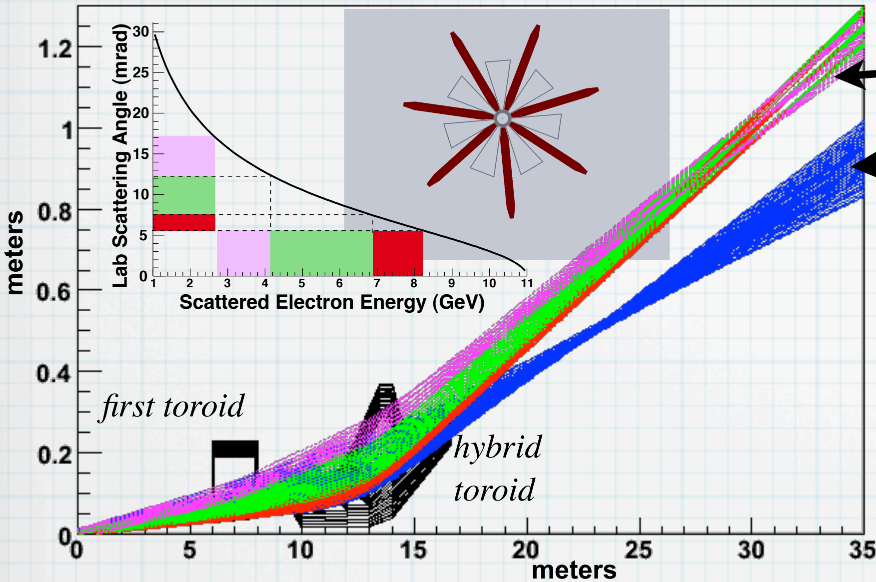

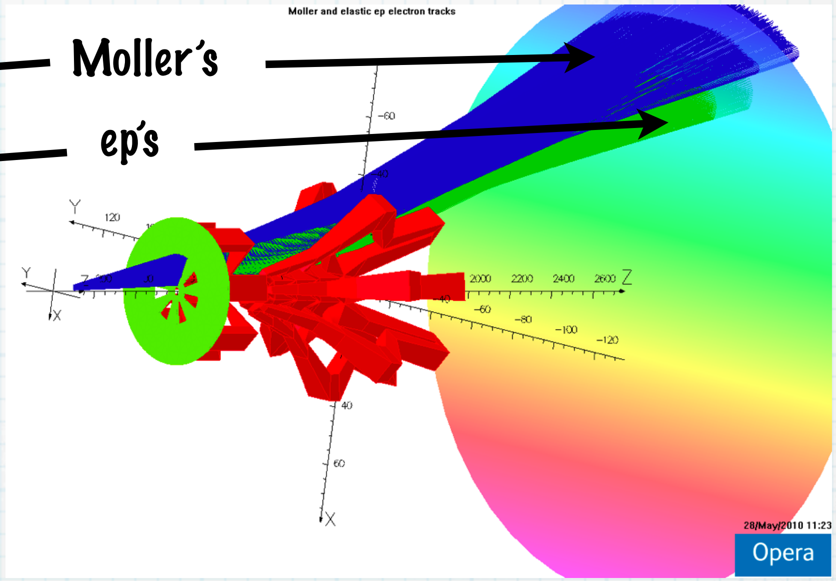

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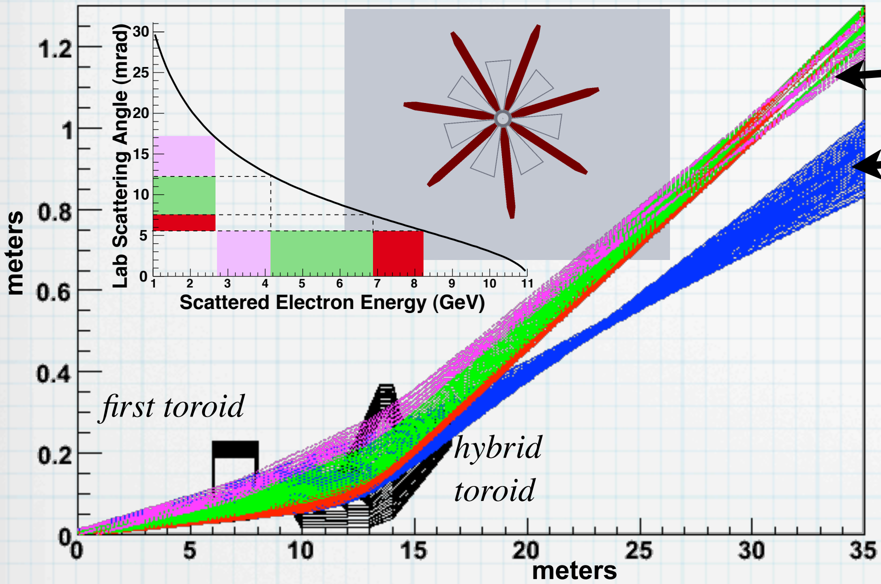

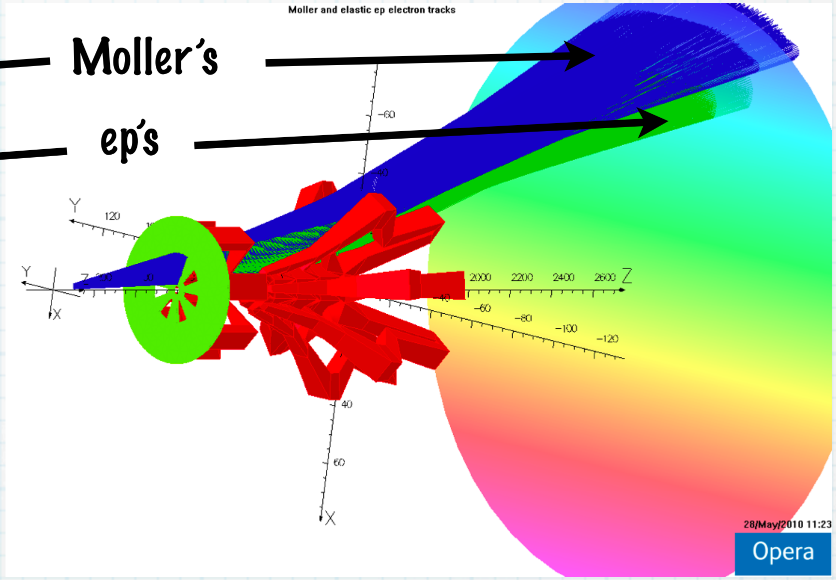

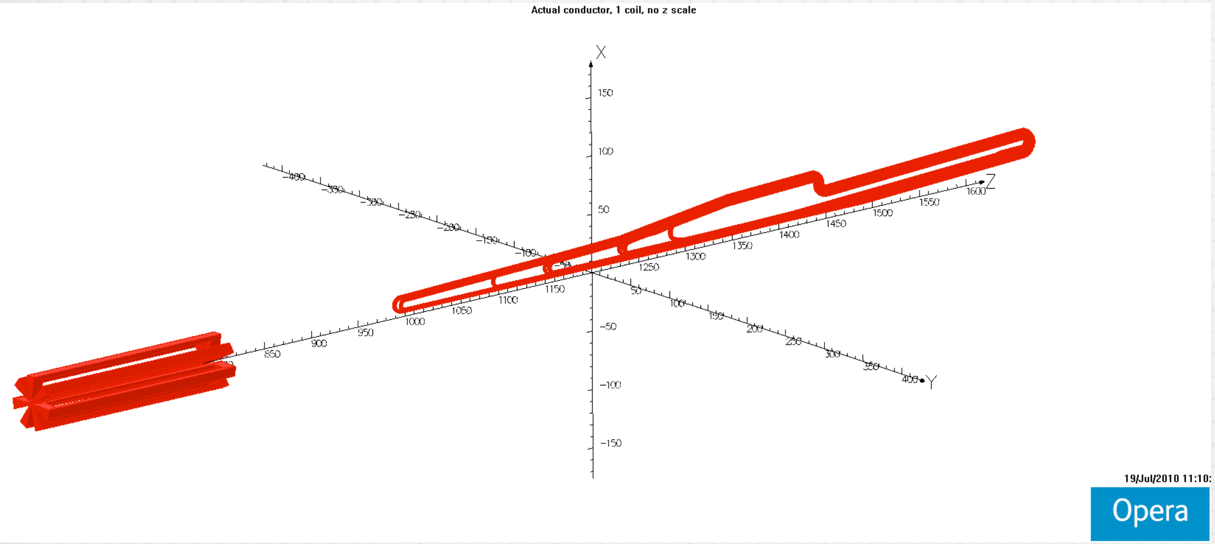

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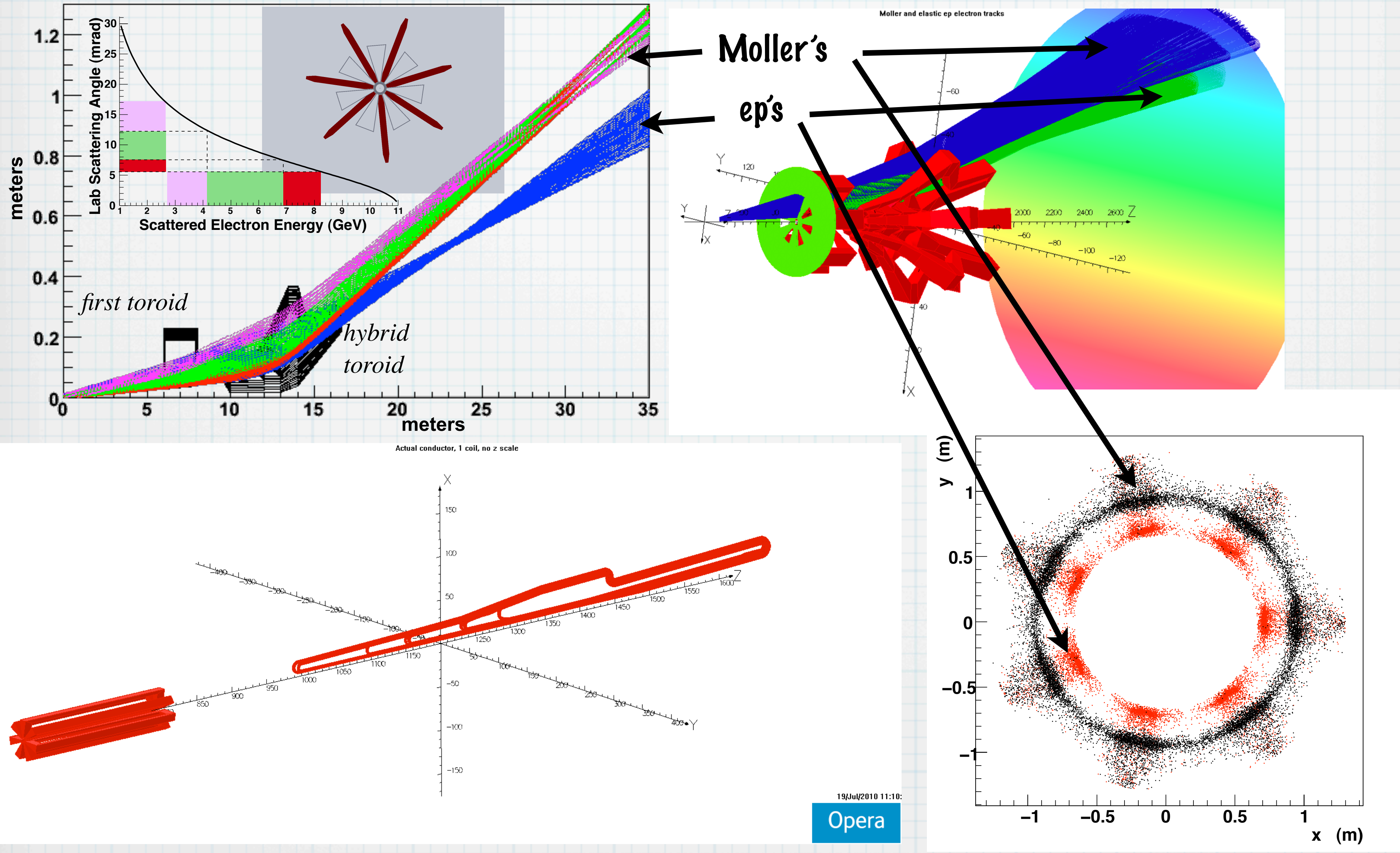

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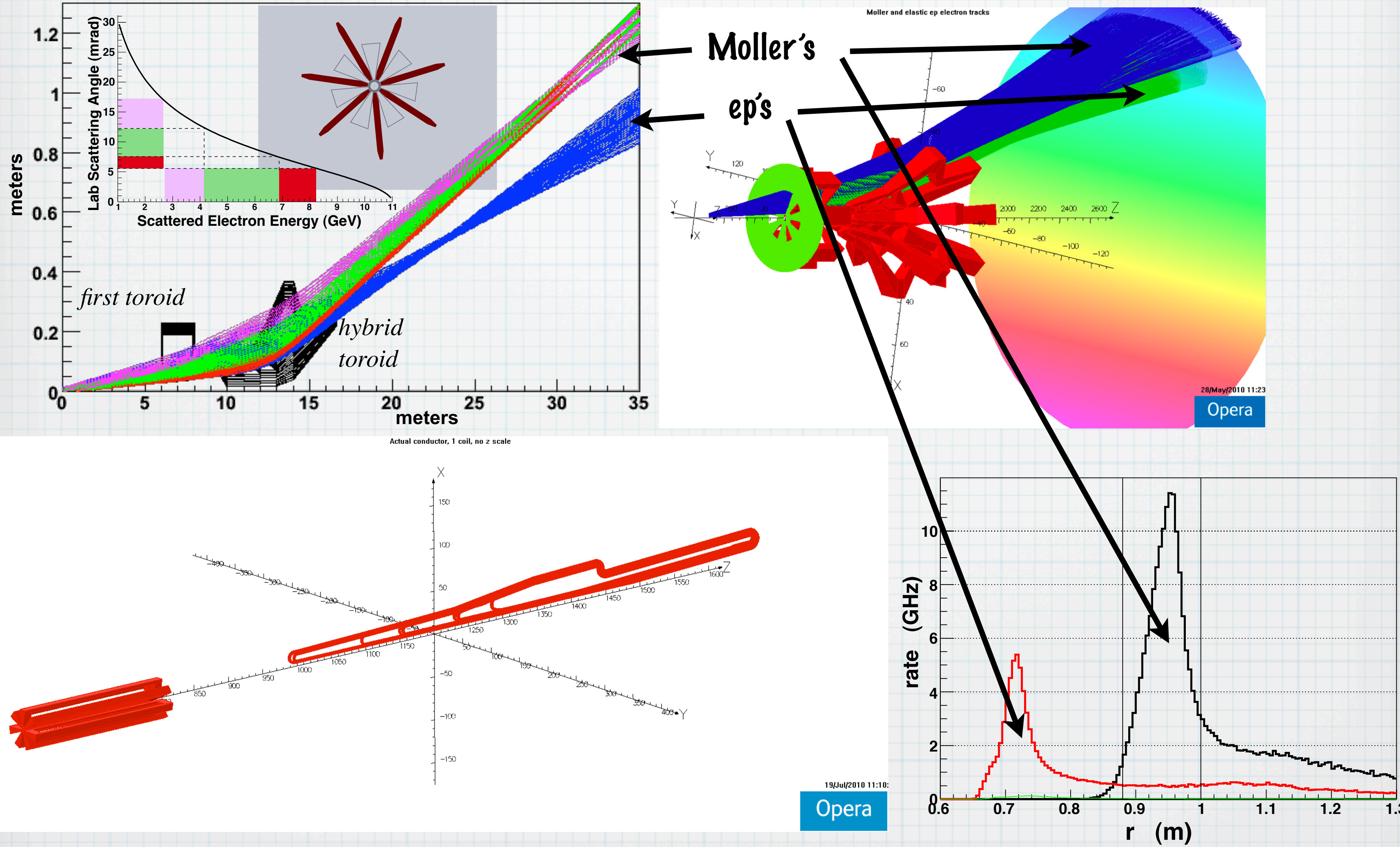
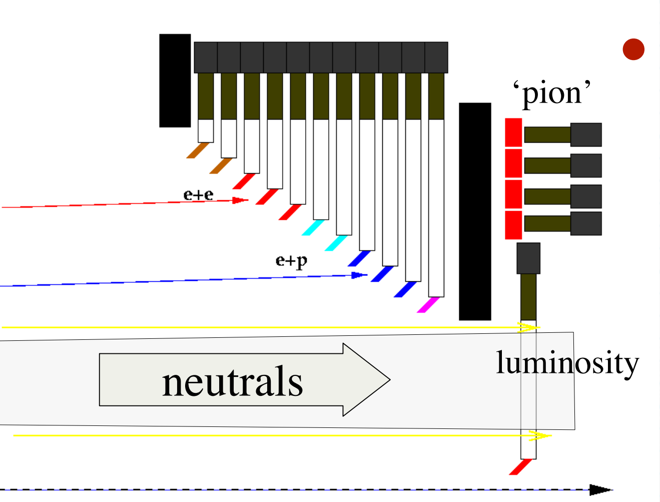


Detector Systems



- **Integrating Detectors:**
  - Moller and e-p Electrons:
    - *radial and azimuthal segmentation*
    - *quartz with air lightguides & PMTs*
  - pions and muons:
    - *quartz sandwich behind shielding*
  - luminosity monitors
    - *beam & target density fluctuations*

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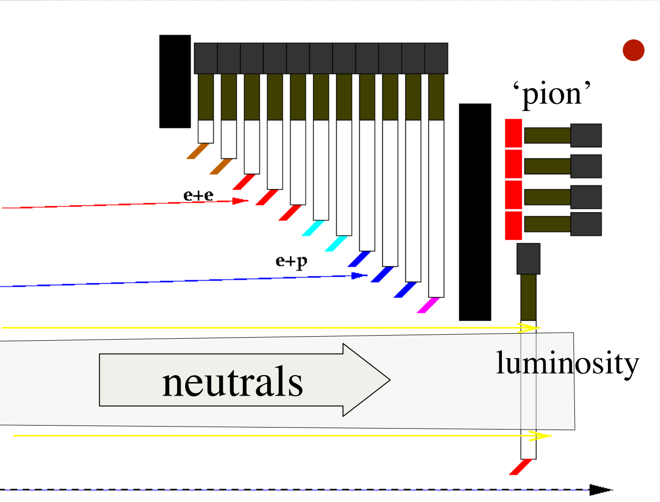

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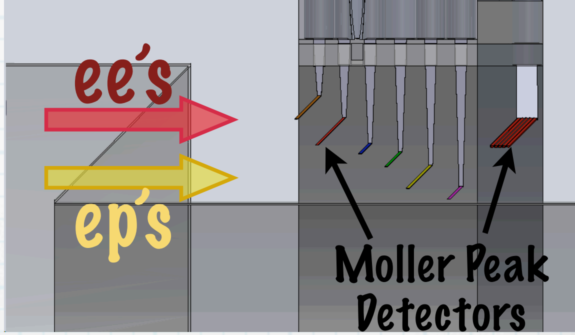
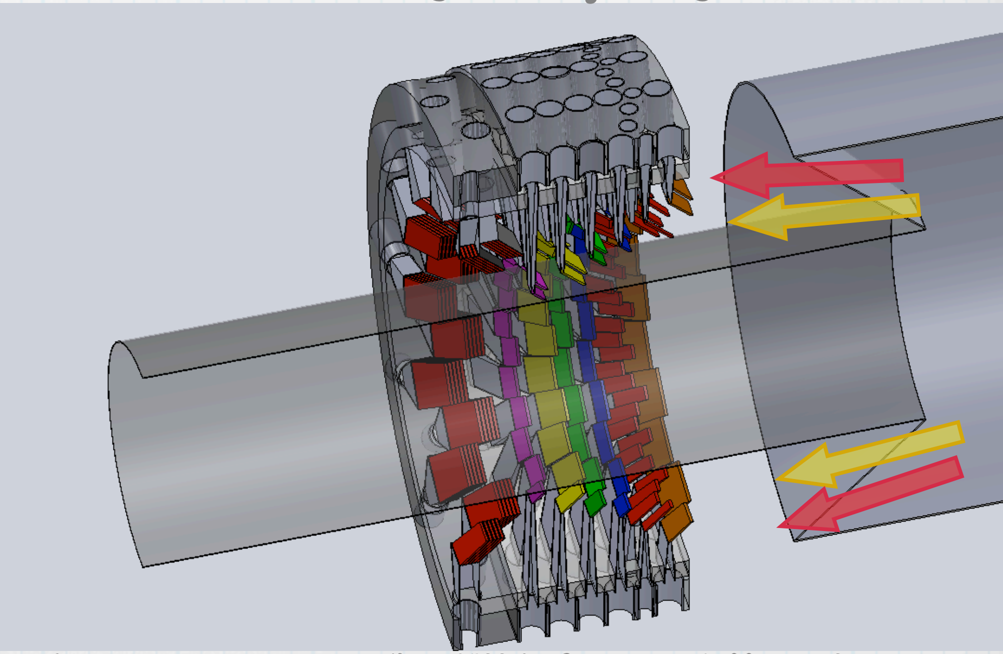
optimized for robust background subtraction



CAD design in progress



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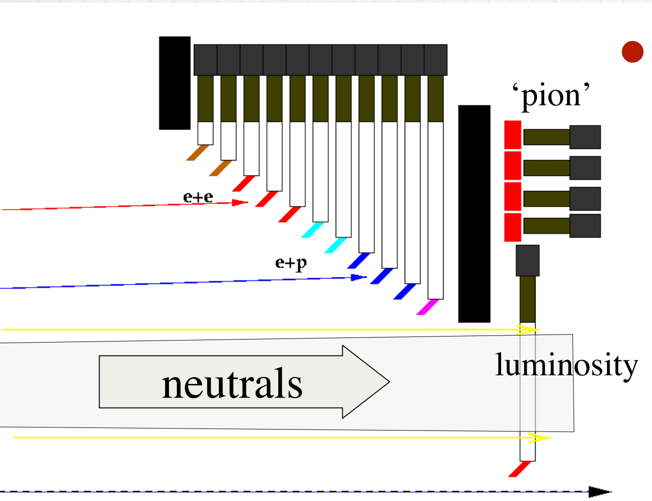

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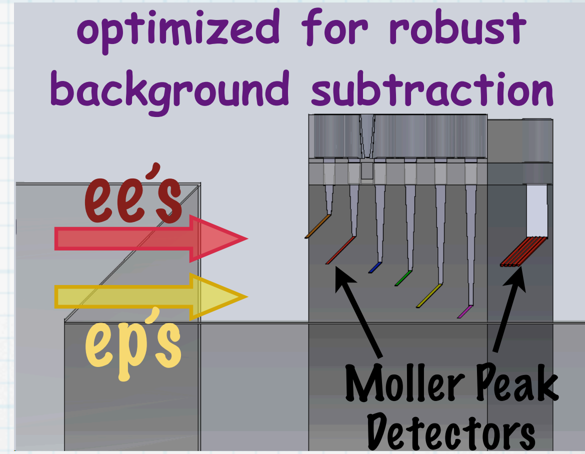

- Auxiliary Detectors
  - Tracking detectors
    - *3 planes of GEMs/Straws*
    - *Critical for systematics/ calibration/debugging*
  - Integrating Scanners
    - *quick checks on stability*

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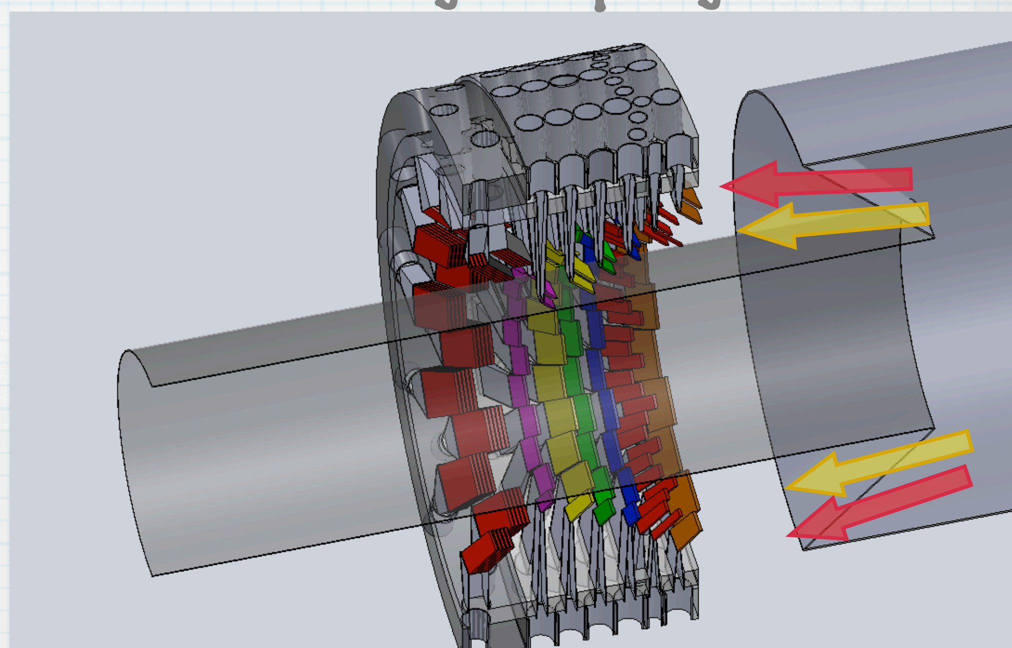

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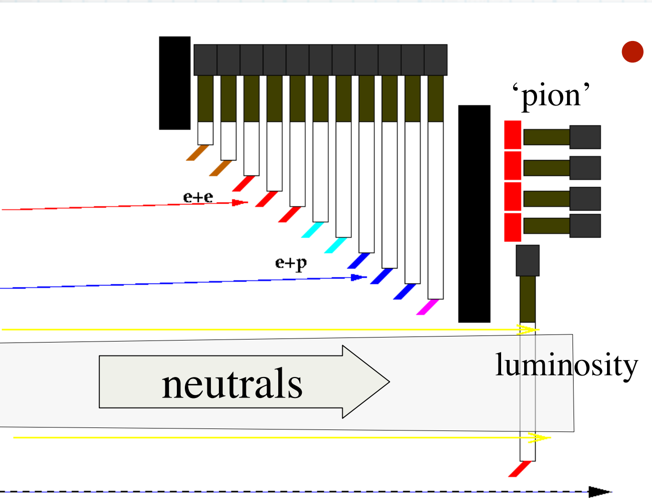

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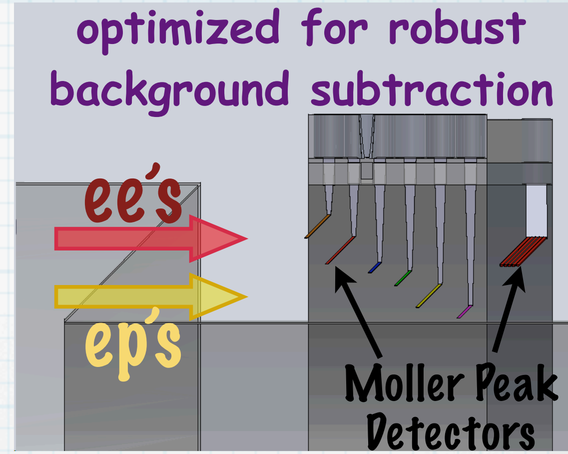

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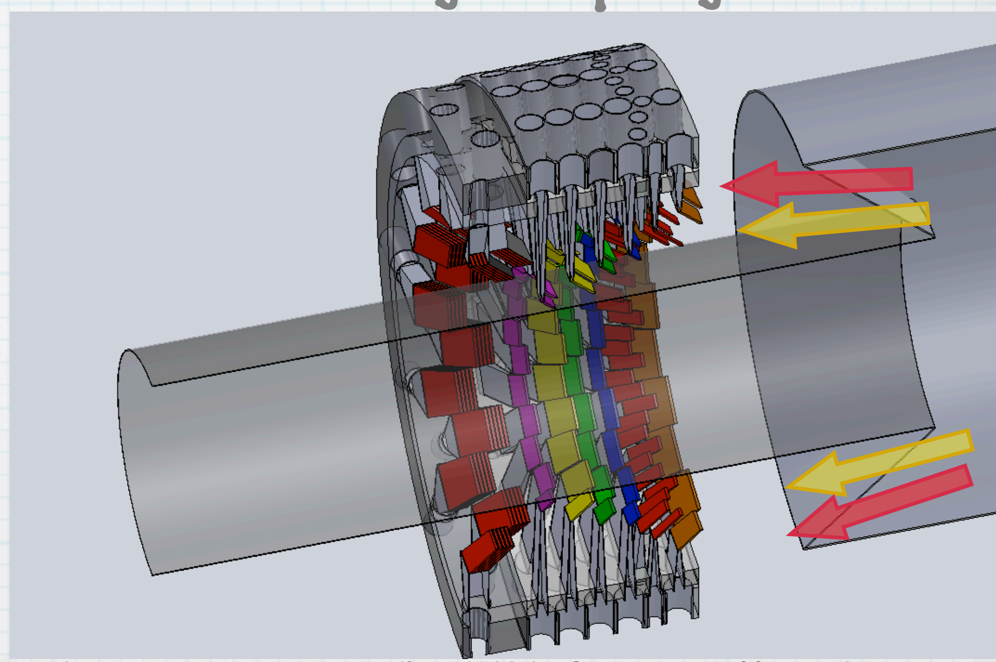

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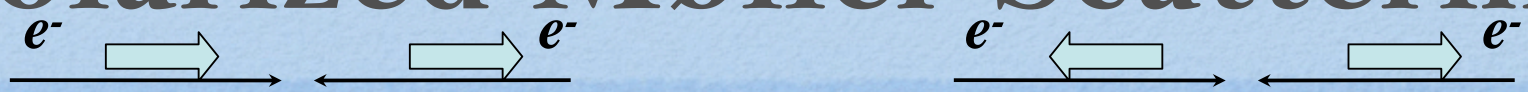
Collaboration physicists will continue to define and optimize the full suite of detectors

mid-70s

Polarized Møller Scattering



ABSTRACT

The longitudinal polarization of the new Yale-SLAC polarized electron beam has been determined at laboratory energies between 6.47 and 19.40 GeV. Spin-dependent elastic electron-electron scattering (Møller scattering) has been found to be a practical technique for polarization measurements at high energies. The

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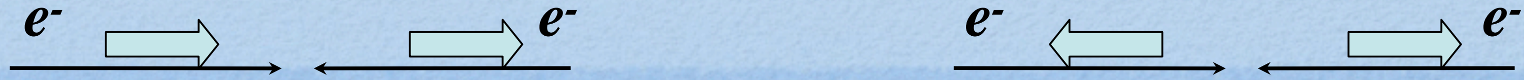

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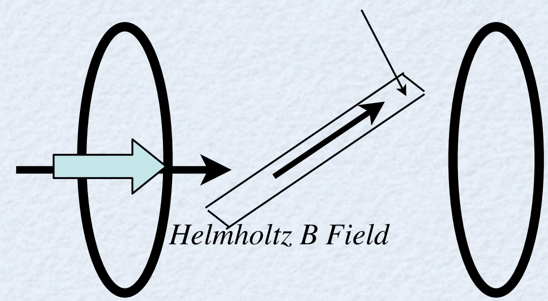

$$\frac{(\sigma_{\uparrow\downarrow} - \sigma_{\downarrow\downarrow})}{(\sigma_{\uparrow\downarrow} + \sigma_{\downarrow\downarrow})} = -\frac{\sin^2\theta(7+\cos^2\theta)}{(3+\cos^2\theta)^2}$$

parity-conserving purely QED effect

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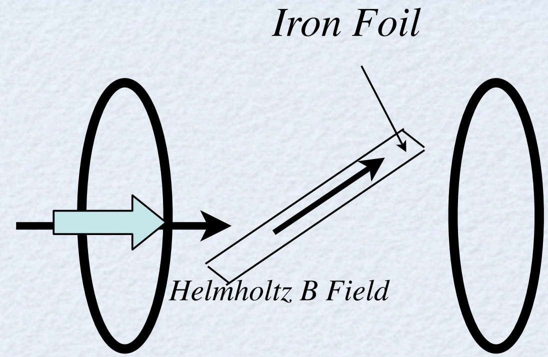

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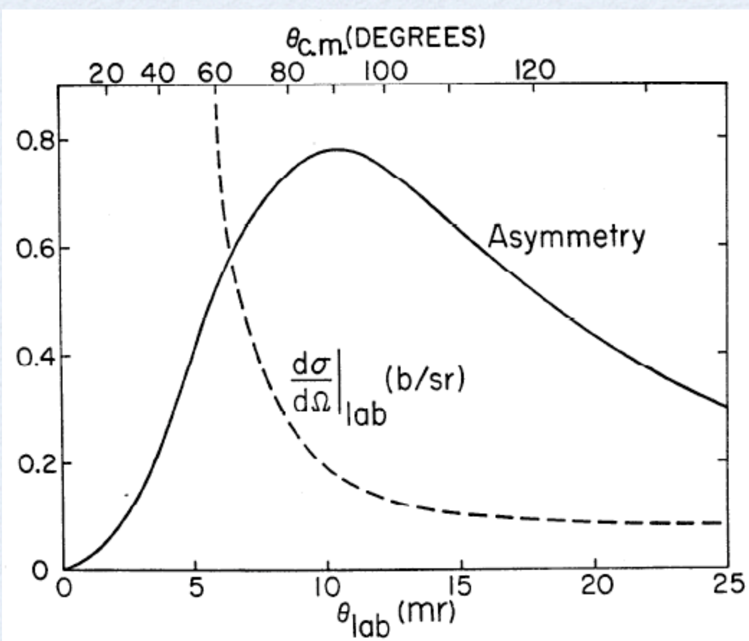

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very forward angle, small COM energy

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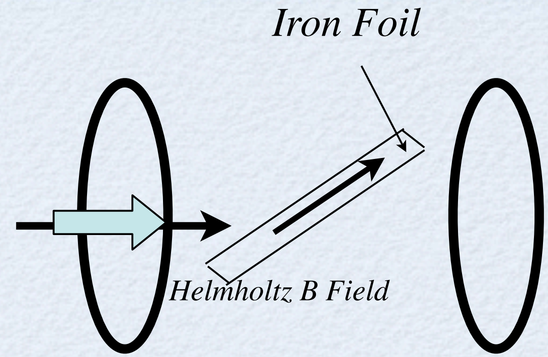

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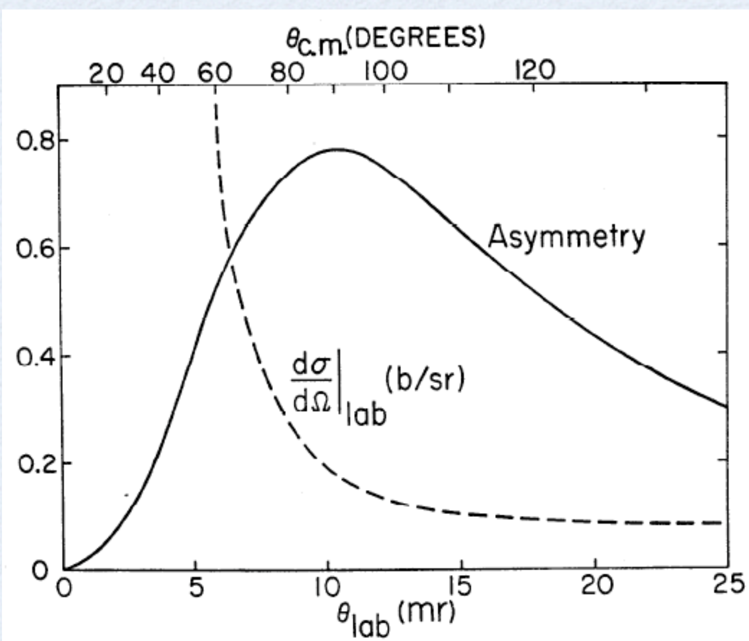

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very forward angle, small COM energy

- polarized target electrons: Fe foil
- Large cross-section; well-known double-spin asymmetry
- Accepted method to measure electron beam polarization

Spectrometer Engineering

We face the usual "chicken and egg" story: *No funding yet, but need engineering before we fine-tune optics, define footprint, estimate cost and risk*

- Magnet Advisory Committee formed
  - George Clark (TRIUMF), Ernie Ihloff (MIT-Bates), Vladimir Kashikhin (Fermilab), Jim Kelsey (MIT-Bates), Dieter Walz (SLAC) & Robin Wines (JLab)

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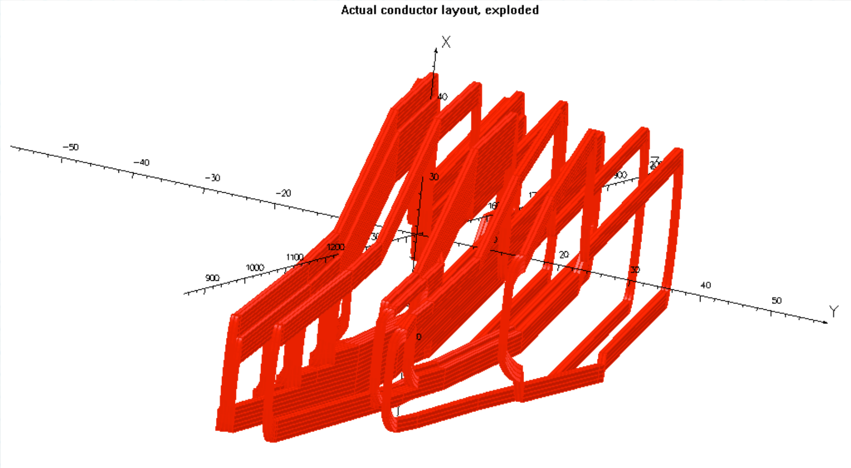
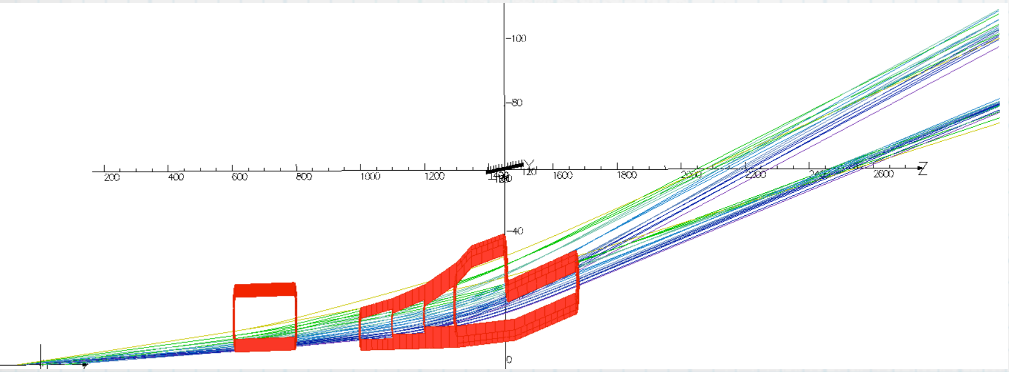
Optics Optimization and Engineering Feasibility

One dedicated postdoc under my supervision with occasional free engineering advice

The hybrid toroid is the heart of the apparatus



Proposal field map achieved with buildable coil configuration



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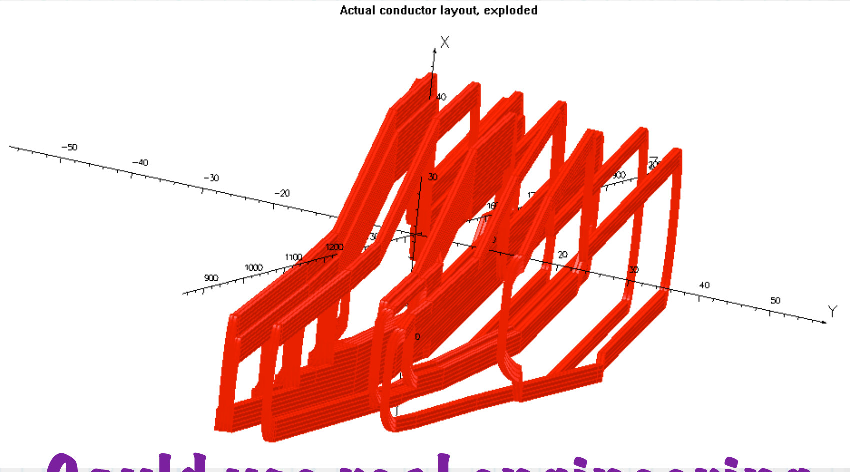

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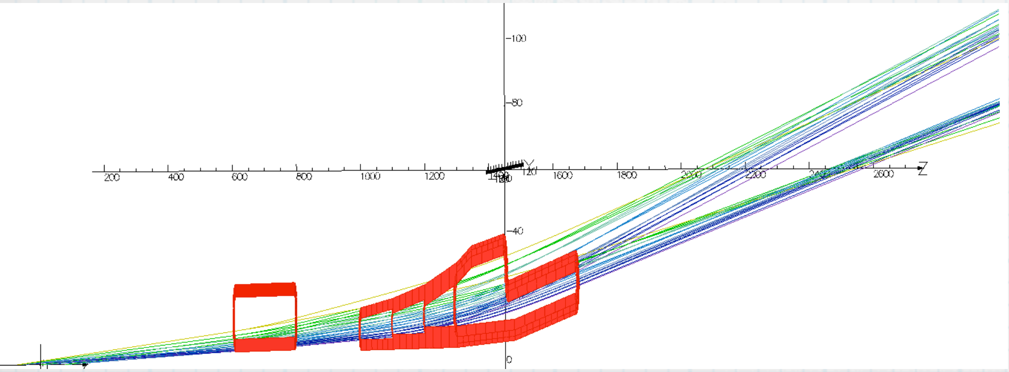
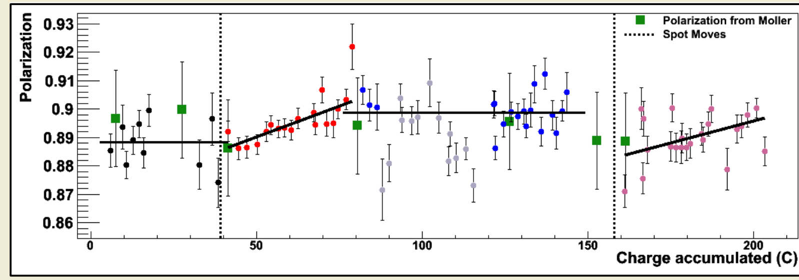


Could use real engineering effort by Summer 2011

HAPPEX-III Error Budget

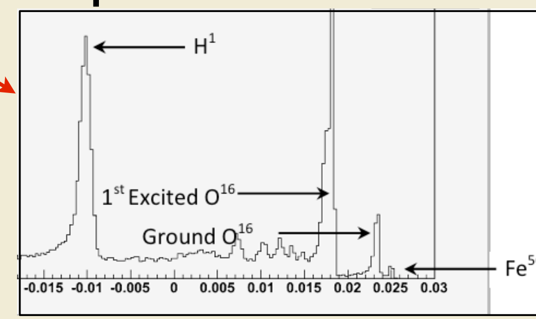
	δA_{PV} (ppm)	$\delta A_{PV} / A_{PV}$
Polarization	0.202	0.85%
Q^2 Measurement	0.160	0.67%
Backgrounds	0.194	0.82%
Linearity	0.129	0.54%
Finite Acceptance	0.048	0.20%
False Asymmetries	0.041	0.17%
Total Systematic	0.353	1.49%
Statistics	0.776	3.27%
Total Experimental	0.853	3.59%

Compton + Moller polarimeters



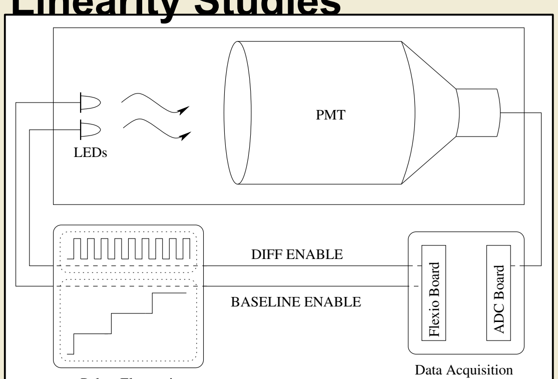
more later from Megan Friend, CMU

Spectrometer Calibration



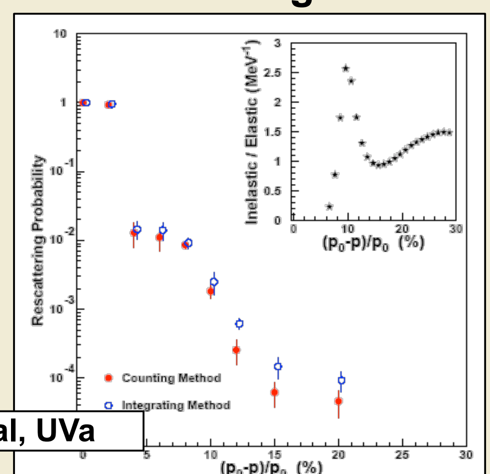
more later from
Kiadtisak Saenboonruang, UVa

Linearity Studies



more later from Rupesh Silwal, UVa

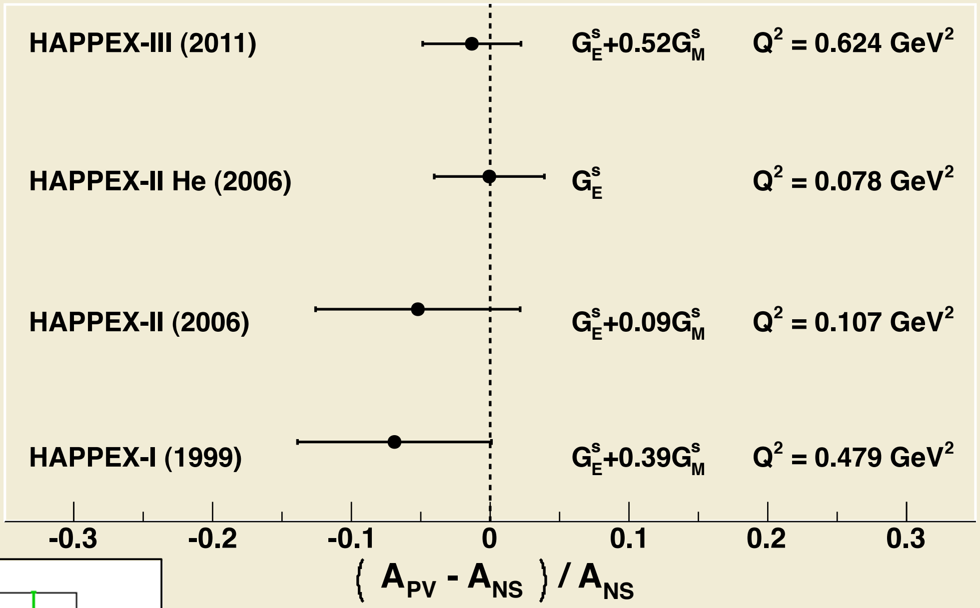
HRS Backgrounds

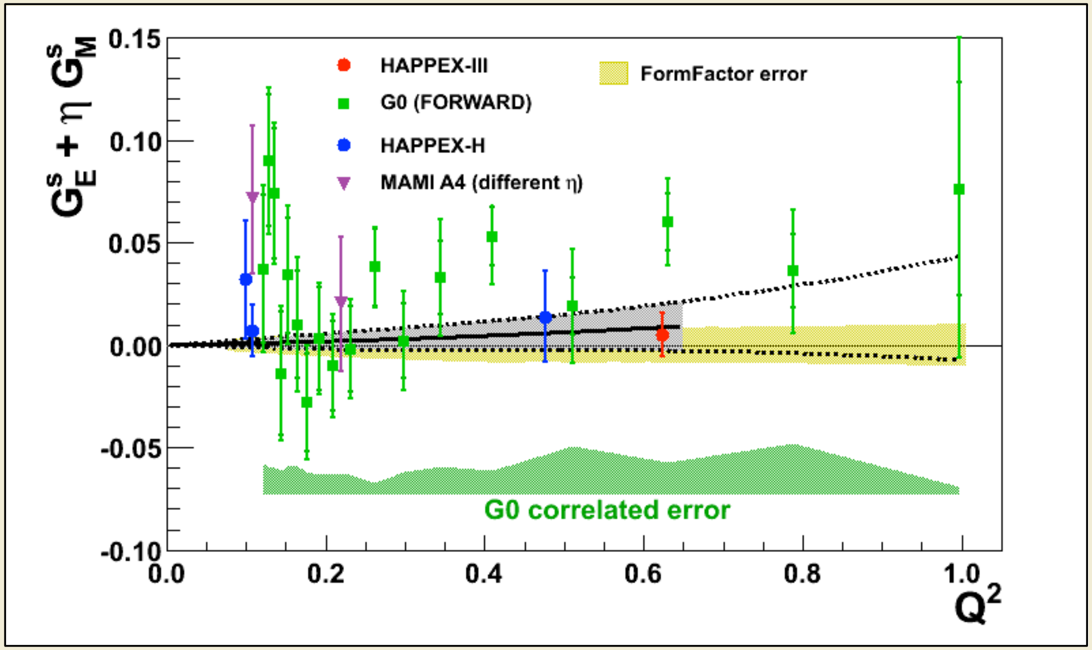


Systematic uncertainties are well controlled - experiment is statistics dominated

Considering only the 4 HAPPEX measurements

- High precision
- Small systematic error
- Clean theoretical interpretation





Nuclear Structure: *Symmetry energy variation with neutron density is a fundamental observable that remains elusive.*

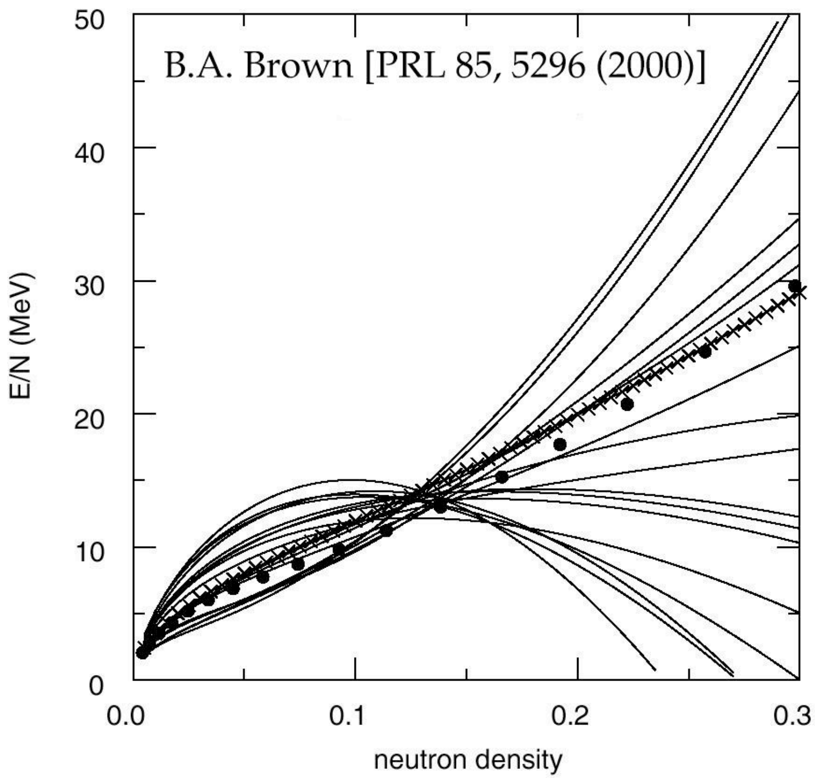


FIG. 2. The neutron EOS for 18 Skyrme parameter sets. The filled circles are the Friedman-Pandharipande (FP) variational calculations and the crosses are SkX. The neutron density is in units of neutron/fm^3.

Reflects poor understanding of symmetry energy of nuclear matter = the energy cost of $N \neq Z$

$$E(n,x) = E(n,x=1/2) + S_\upsilon(n)(1-2x^2)$$

n = n.m. density

x = ratio proton/neutrons

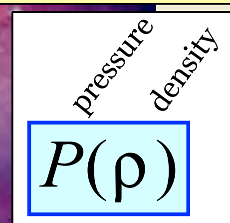
- Slope unconstrained by data
- Adding R_n from ^{208}Pb will eliminate the dispersion in the plot.

Slide adapted from J. Piekarewicz

From ^{208}Pb to a Neutron Star

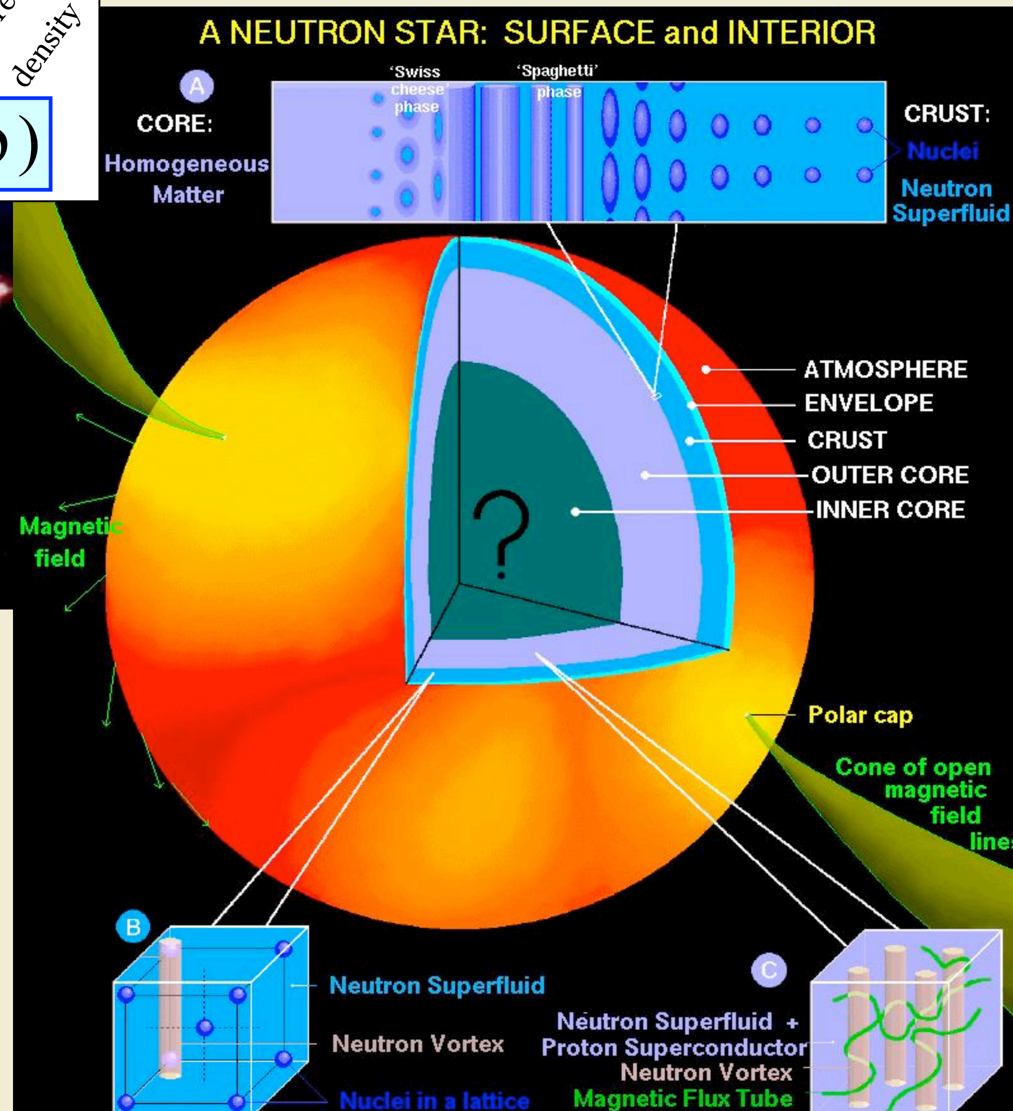
Crab Nebula

R_n calibrates the equation of state of neutron rich matter



Crust Thickness

Explain Glitches in Pulsar Frequency ?



Combine PREX R_n with observed neutron star radii

Phase Transition to "Exotic" Core ?

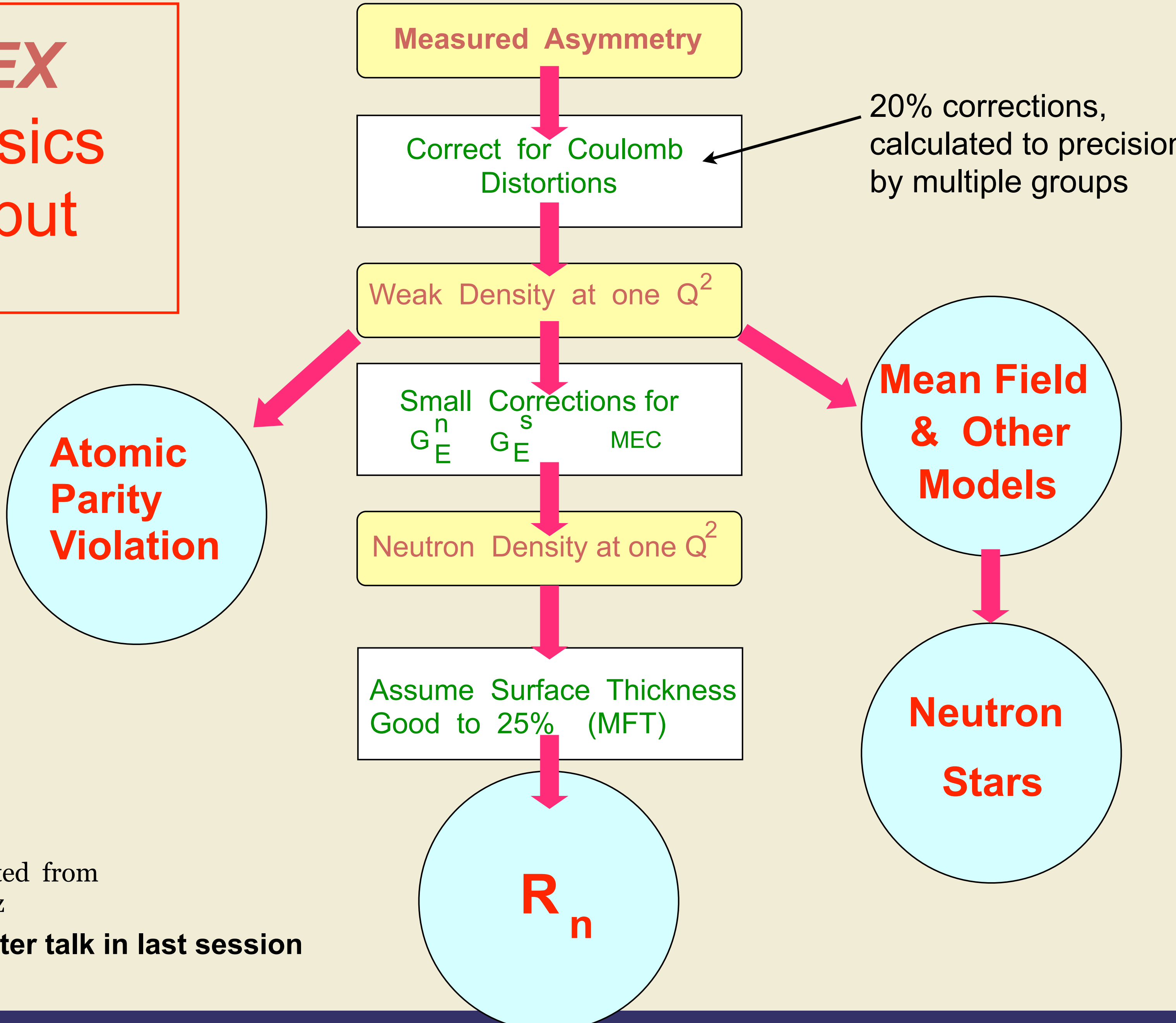
Strange star ? Quark Star ?

Some neutron stars seem too cold

Cooling by neutrino emission (URCA)

$R_n - R_p > 0.2$ fm URCA probable, else not

PREX Physics Output



Slide adapted from
C. Horowitz

see later talk in last session

Challenging Experiment

Similar to the HAPPEX measurements
- Use Hall A spectrometers
- integrating technique

10X more precise than any previous e$^-$-nucleus scattering!

Beam False Asymmetries

Source optimization - reduce position difference and spot-size asymmetry

Injector magnetic spin manipulation

New modulation system for calibrating corrections

Transverse Asymmetry

see later talk by Bob Michaels

Electronics noise

new low-noise ADCs

Ultimate goal:

20 ppb absolute measurement

3% relative error

$\delta(A_{PV})/A_{PV} \sim 3\%$

$\delta(R_n)/R_n \sim 1\%$

see later talk by Luis Mercado

Target survivability

Precise kinematics calibration

Water cell calibration

High rate tracking with GEMS

Low current beam position monitors

Low energy electron beam polarimetry

Compton Polarimeter

upgrade IR to Green light

Integrating photon detection

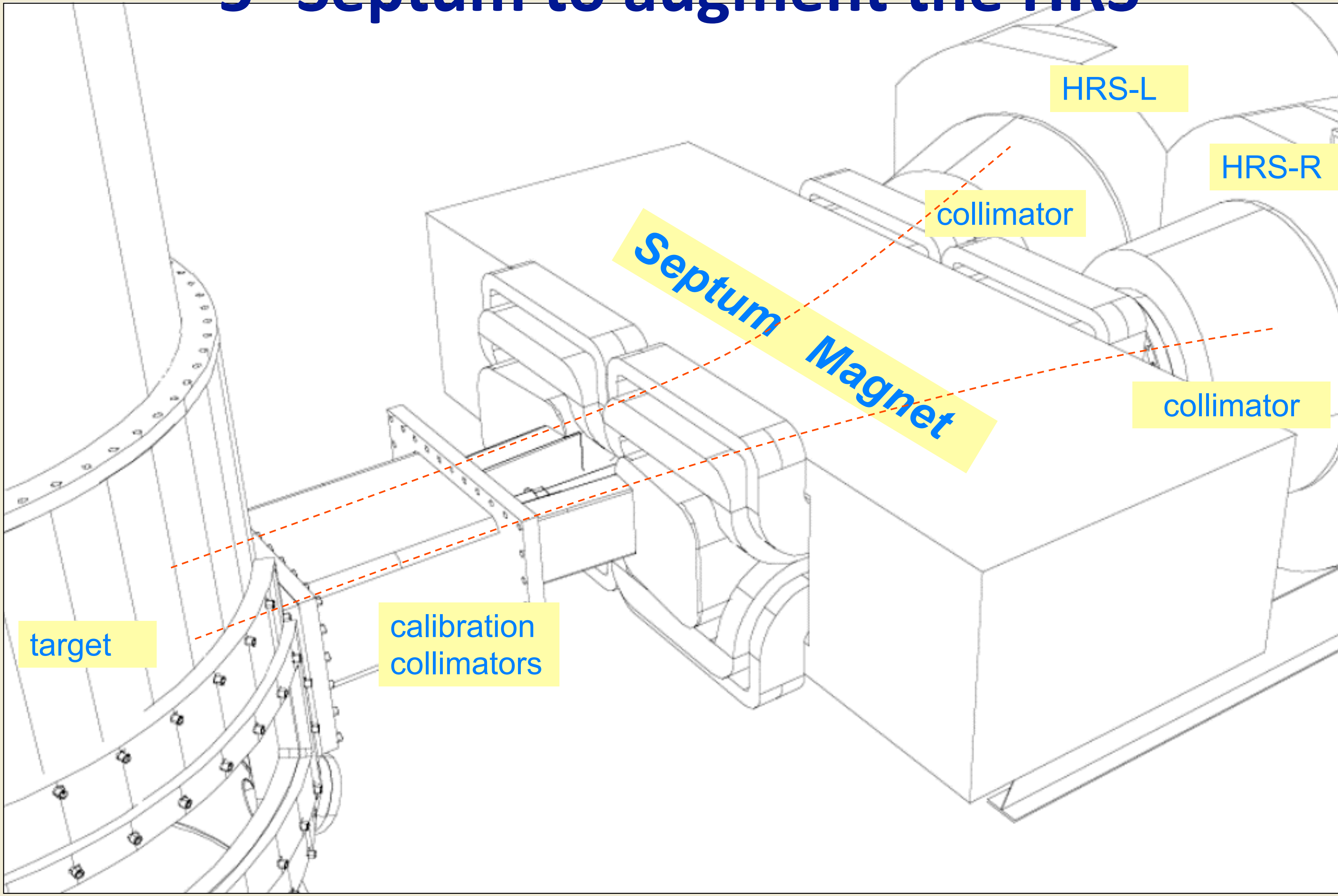
Moller Polarimeter

upgrade to SC magnet

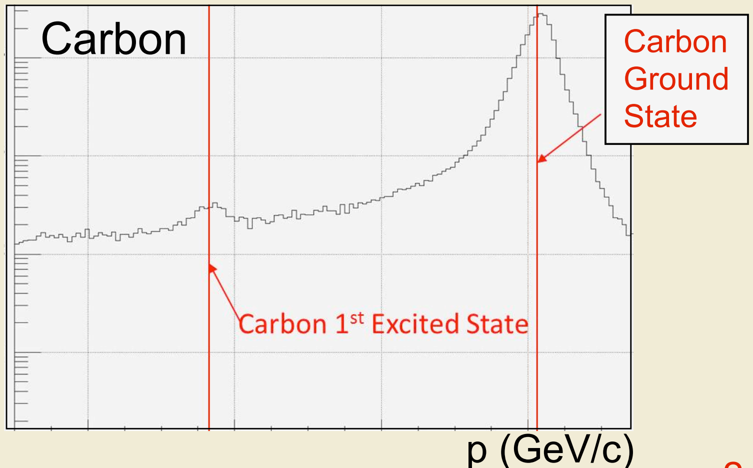
FADC DAQ upgrade

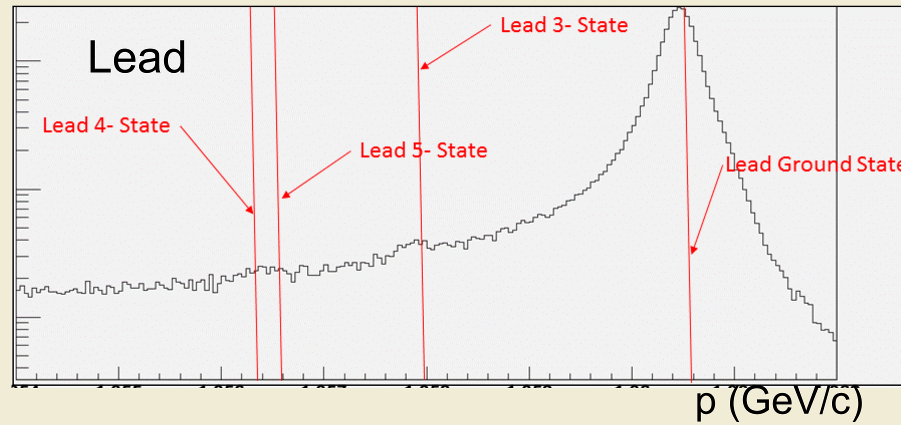
see later talk by Zafar Ahmed

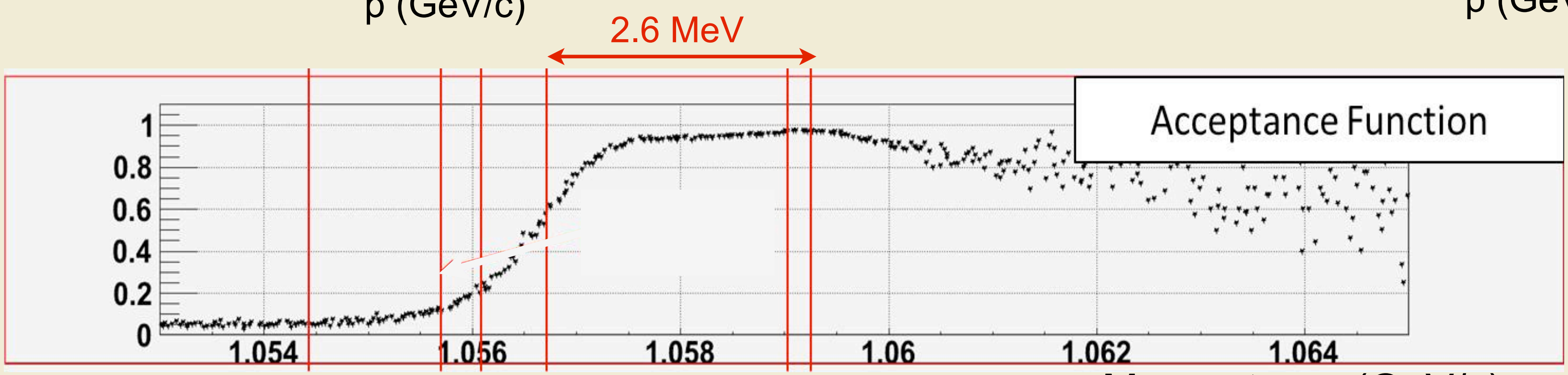
5º Septum to augment the HRS



High Resolution Spectrometer

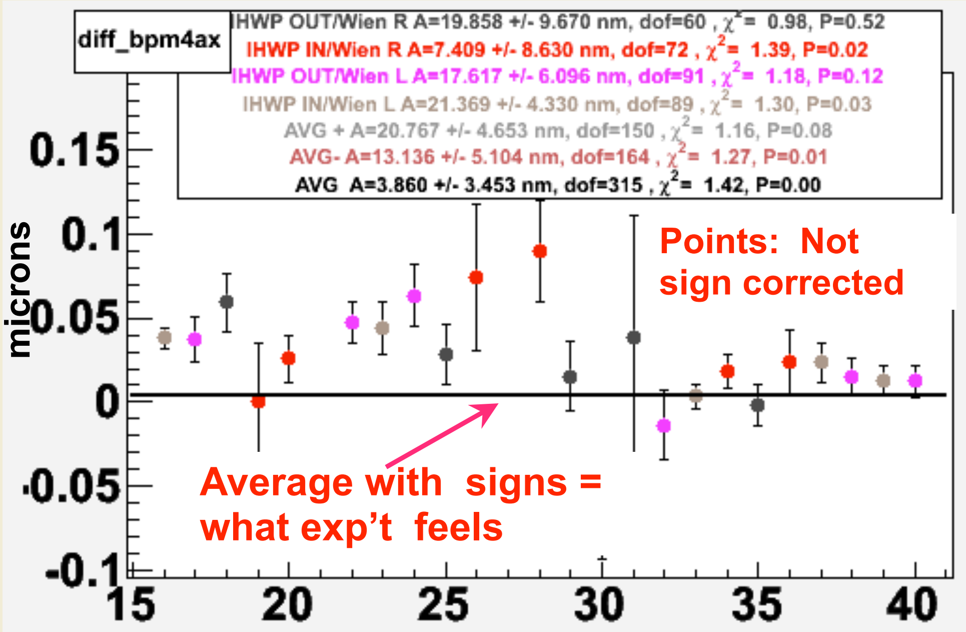






Detector integrates the elastic peak.
Backgrounds from inelastics are suppressed.

Negligible contributions from inelastic events rescattering in spectrometer

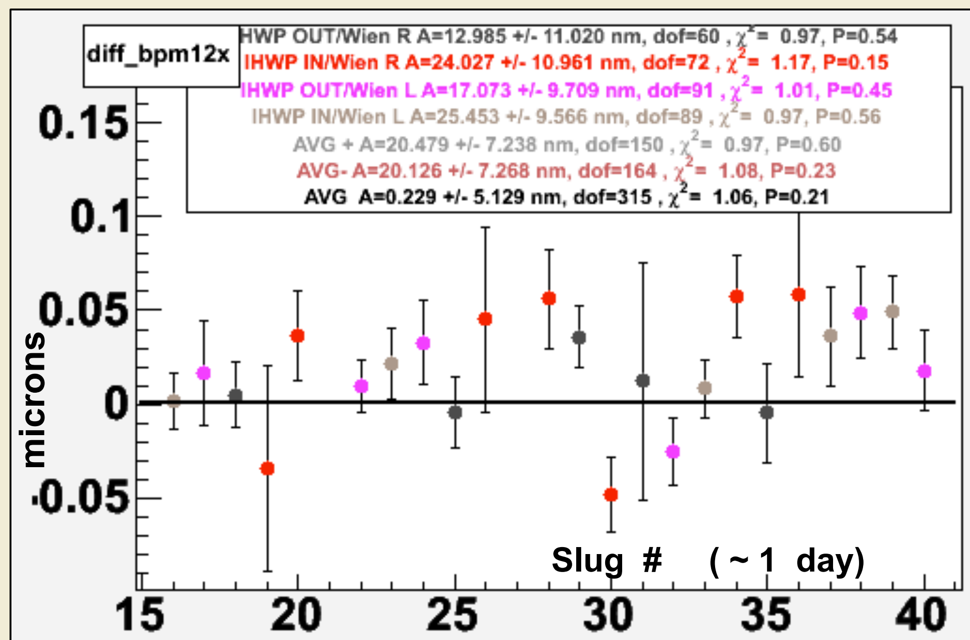


Parity Quality Beam

Helicity – Correlated Position Differences **<** **~ 4 nm**

$$< X_R - X_L > \quad for\ helicity\ L, R$$

Injector spin manipulation proved important for cancellation



Systematic Errors

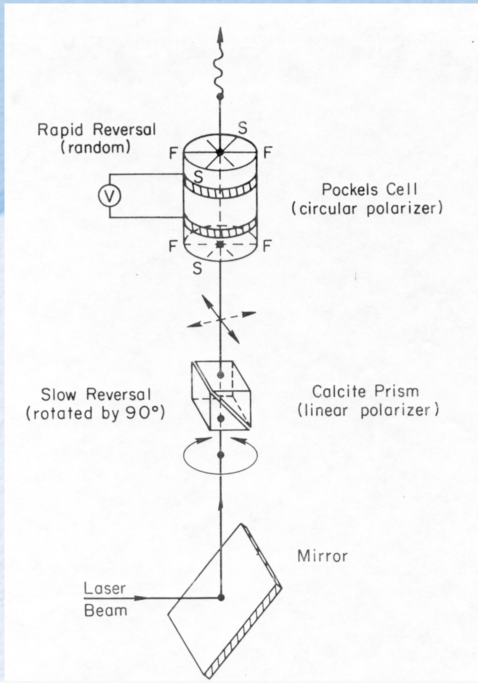
Error Source	Absolute (ppm)	Relative (%)
Polarization (1)	0.0071	1.1
Beam Asymmetries (2)	0.0072	1.1
Detector Linearity	0.0071	1.1
BCM Linearity	0.0010	0.2
Rescattering	0.0001	0
Transverse Polarization	0.0012	0.2
Q^2 (1)	0.0028	0.4
Target Thickness	0.0005	0.1
^{12}C Asymmetry (2)	0.0025	0.4
Inelastic States	0	0
TOTAL	**0.0130**	**2.0**

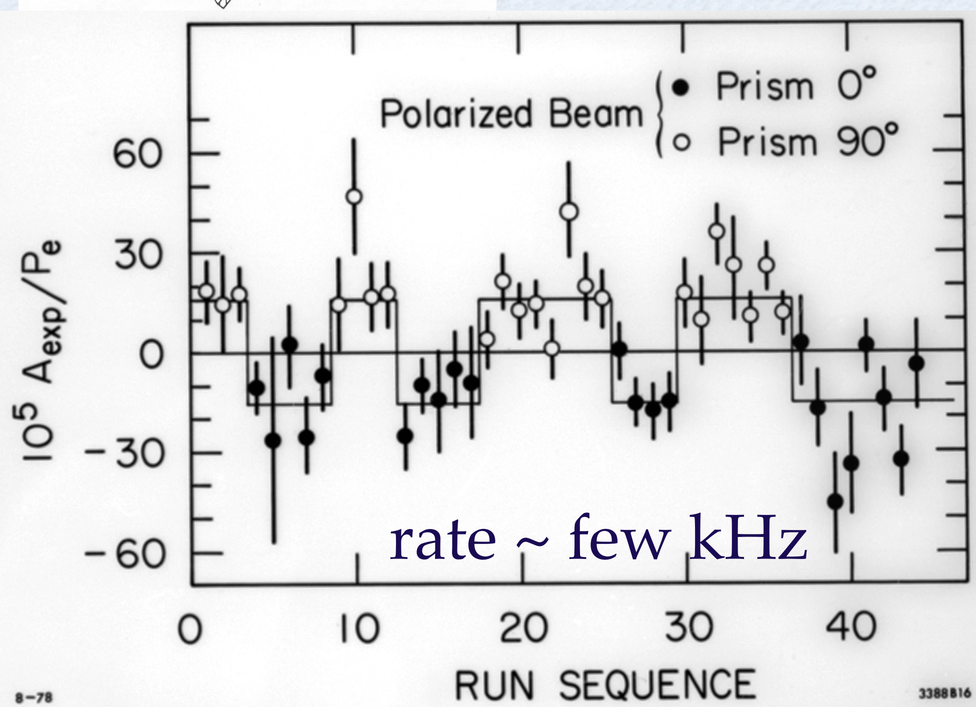
(1) **Normalization Correction** applied

(2) **Nonzero correction** (the rest assumed zero)

Landmark Result

E122 Data

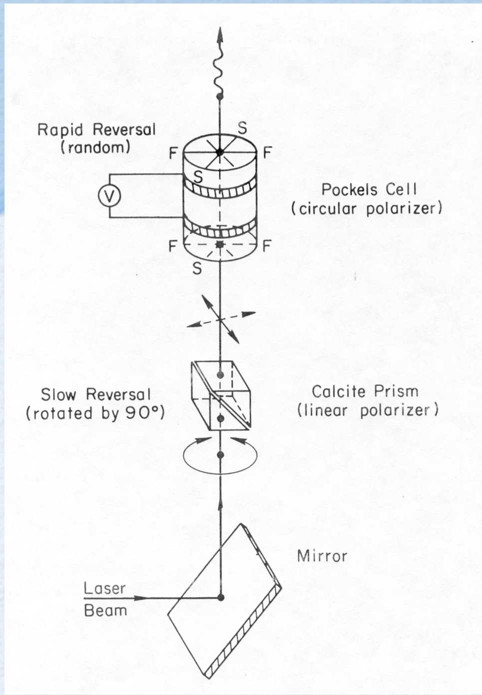


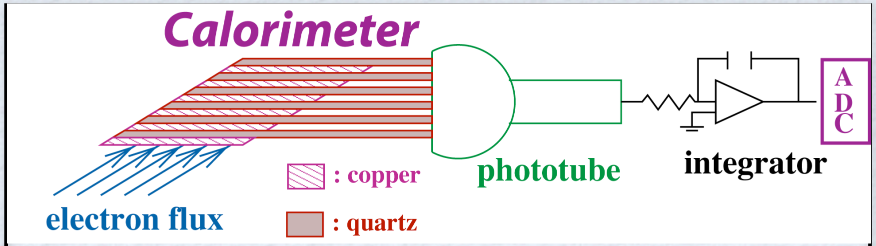


rate ~ few kHz

Landmark Result

E122 Data



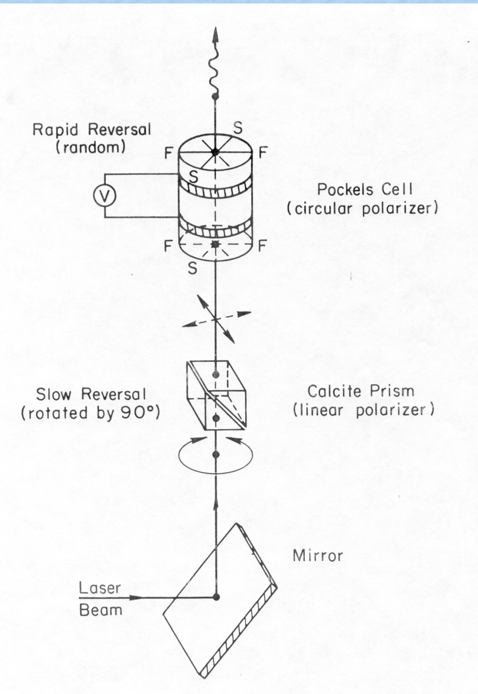


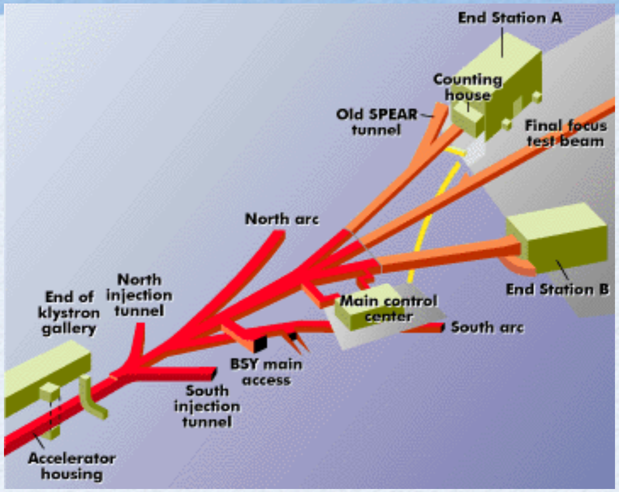
"Flux Integration":
Allows counting at high rates

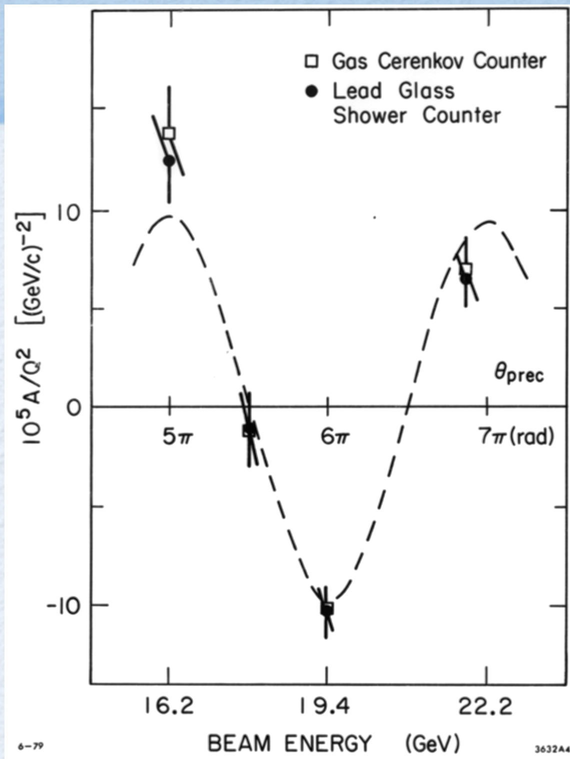
Spectrometer directs flux to background-free region

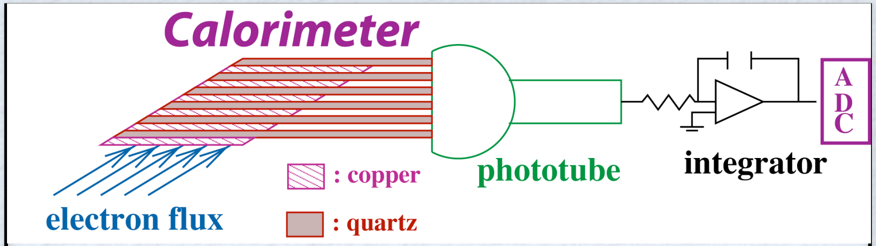
Landmark Result

E122 Data









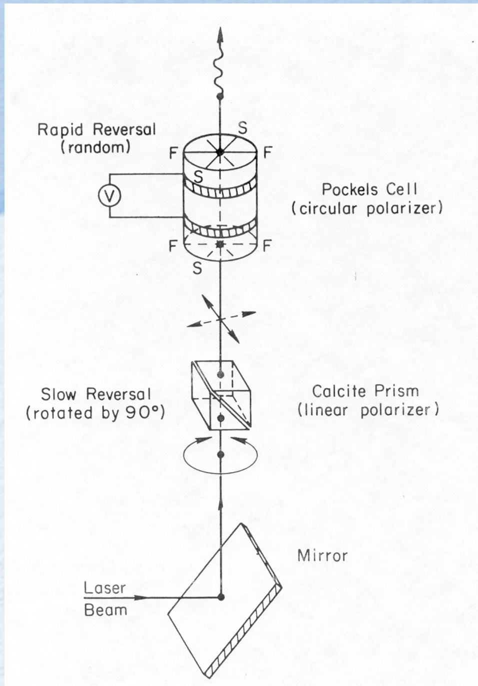
"Flux Integration":
Allows counting at high rates

Spectrometer directs flux to background-free region

$$\theta_{prec} \sim \left(\frac{E}{m}\right)\left(\frac{g-2}{2}\right)$$

Landmark Result

E122 Data



PARITY NON-CONSERVATION IN INELASTIC ELECTRON SCATTERING*

C. Y. Prescott, W. B. Atwood, R. L. A. Cottrell, H. DeStaebler,
Edward L. Garwin, A. Gonidec,** R. H. Miller, L. S. Rochester, T. Sato†
D. J. Sherden, C. K. Sinclair, S. Stein, R. E. Taylor

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Yale University
New Haven, Connecticut 06520

M. G. Borghini
CERN
Geneva, Switzerland

K. Lübelsmeyer
Technische Hochschule Aachen
Aachen, West Germany

W. Jentschke
II. Inst. für Experimentalphysik
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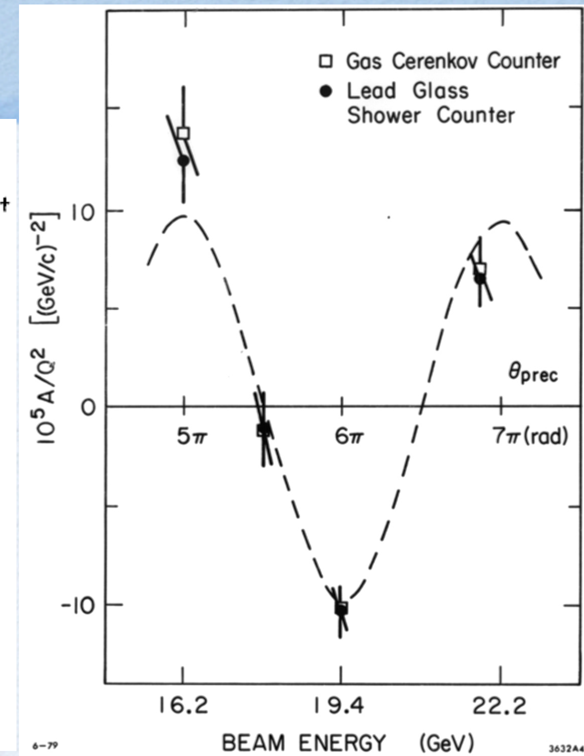


ABSTRACT

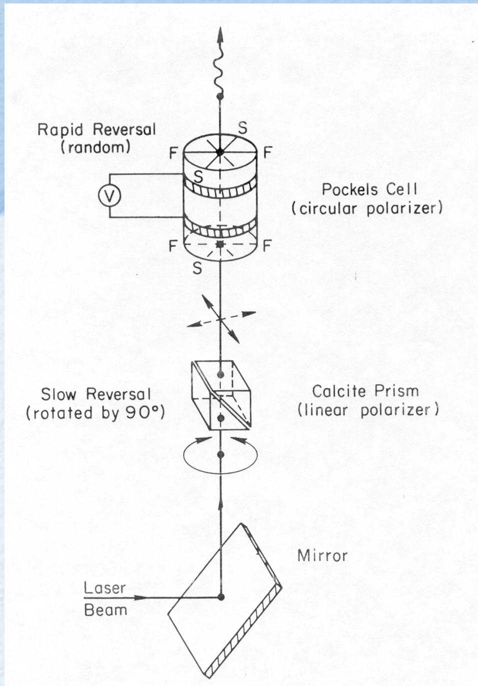
We have measured parity violating asymmetries in the inelastic scattering of longitudinally polarized electrons from deuterium and hydrogen. For deuterium near $Q^2 = 1.6$ (GeV/c)^2 the asymmetry is $(-9.5 \times 10^{-5})\, Q^2$ with statistical and systematic uncertainties each about 10%.

$$\theta_{prec} \sim \left(\frac{E}{m}\right)\left(\frac{g-2}{2}\right)$$

- *Parity Violation in Weak Neutral Current Interactions*
- *$\sin^2\theta_W = 0.224 \pm 0.020$: same as in neutrino scattering*

Landmark Result

E122 Data



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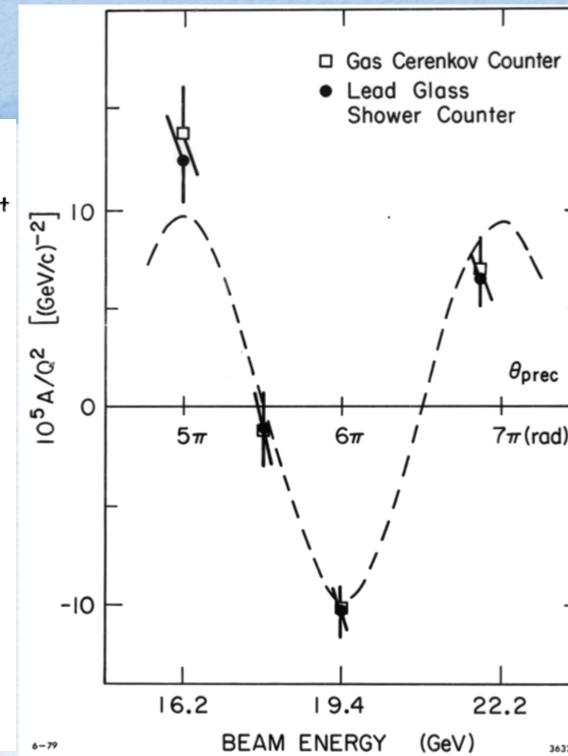

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$$\theta_{prec} \sim \left(\frac{E}{m}\right)\left(\frac{g-2}{2}\right)$$

Glashow, Weinberg, Salam Nobel Prize awarded in 1979

- *Parity Violation in Weak Neutral Current Interactions*
- *$\sin^2\theta_W = 0.224 \pm 0.020$: same as in neutrino scattering*

mid-1990s

The Standard Model

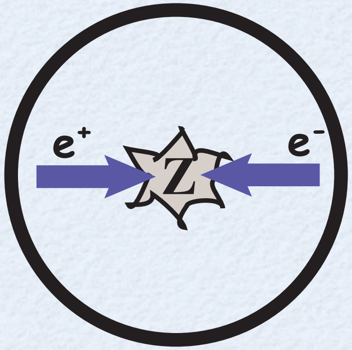
of Electroweak (EW) Interactions

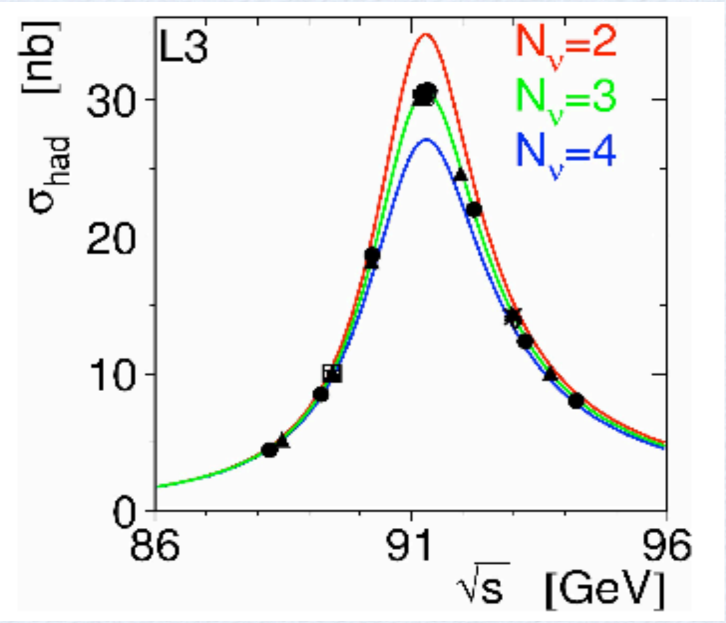
For electroweak (EW) interactions, there are three parameters needed:

1. Scale of electromagnetism i.e. the fine structure constant
2. Scale of the weak interaction i.e. the W boson mass
3. Weak mixing angle i.e. the ratio of W and Z boson masses

Parameters are chosen from three precise experimental measurements:

1. **electron g-2**
2. **The muon lifetime**
3. **The Z line shape**



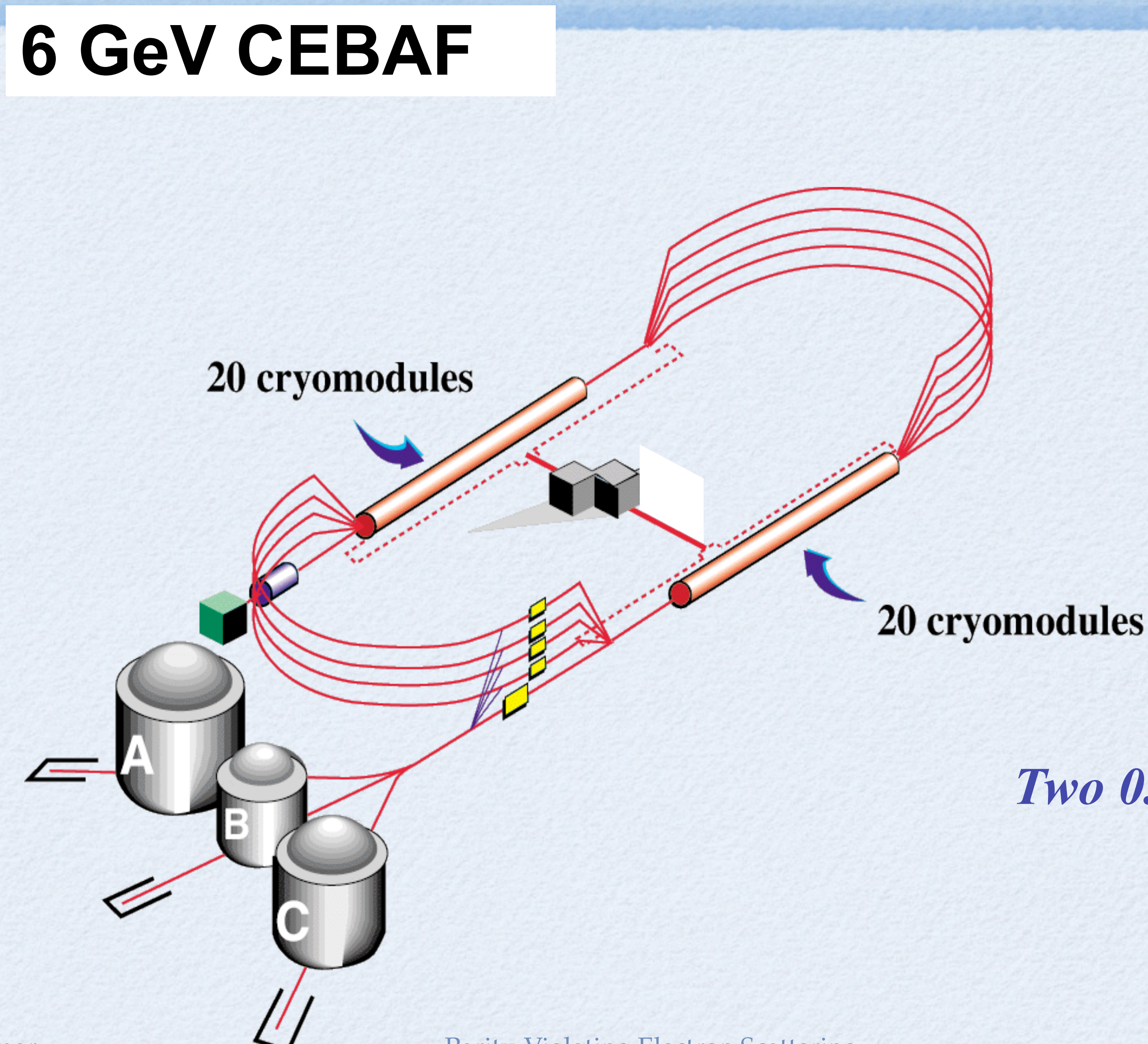


e^+e^- colliders

LEP (CERN) and SLC (SLAC)

$$e^+e^- \rightarrow Z^0 \rightarrow l^+l^-, q\bar{q}$$

12 GeV Upgrade at JLab



Two 0.6 GV linacs

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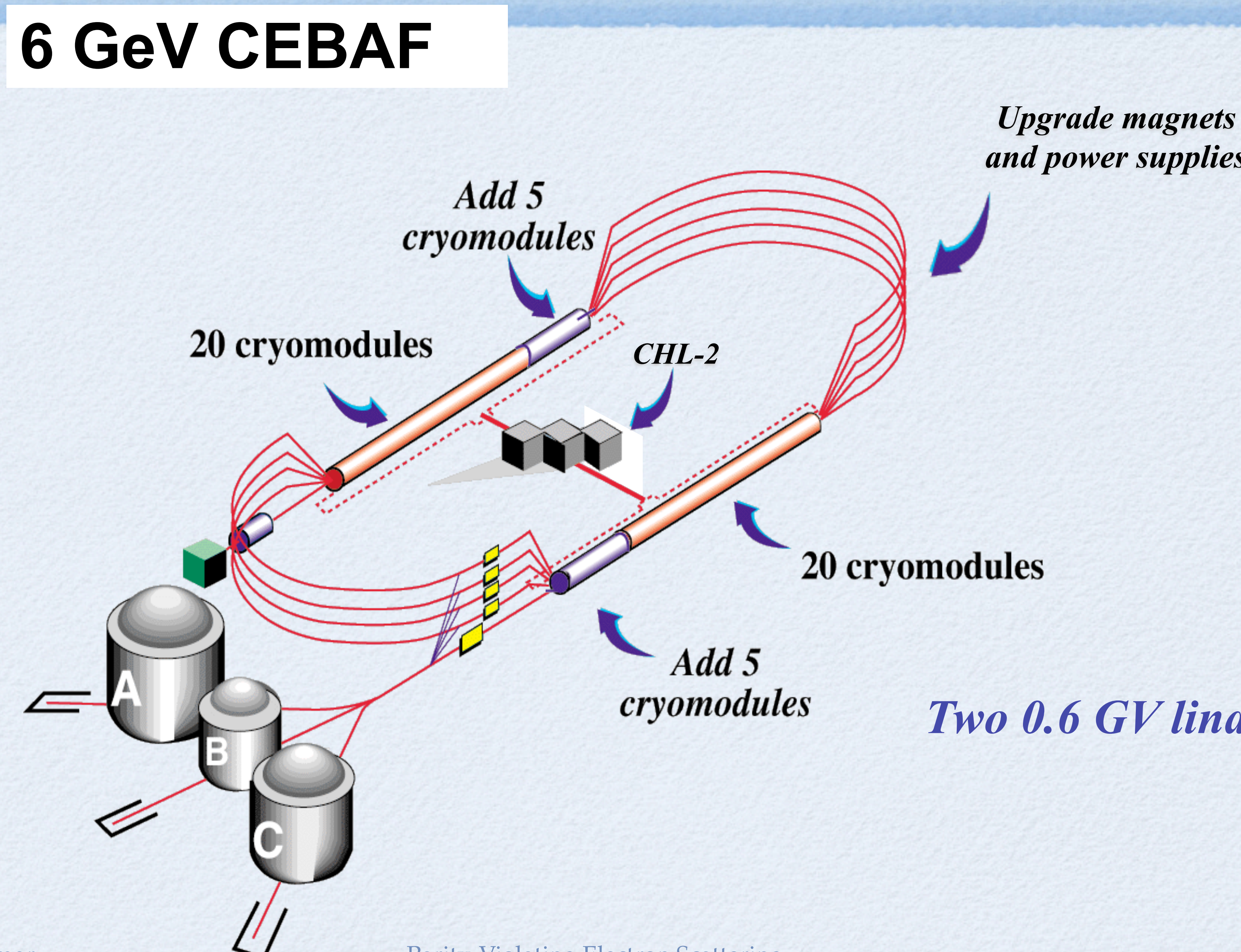

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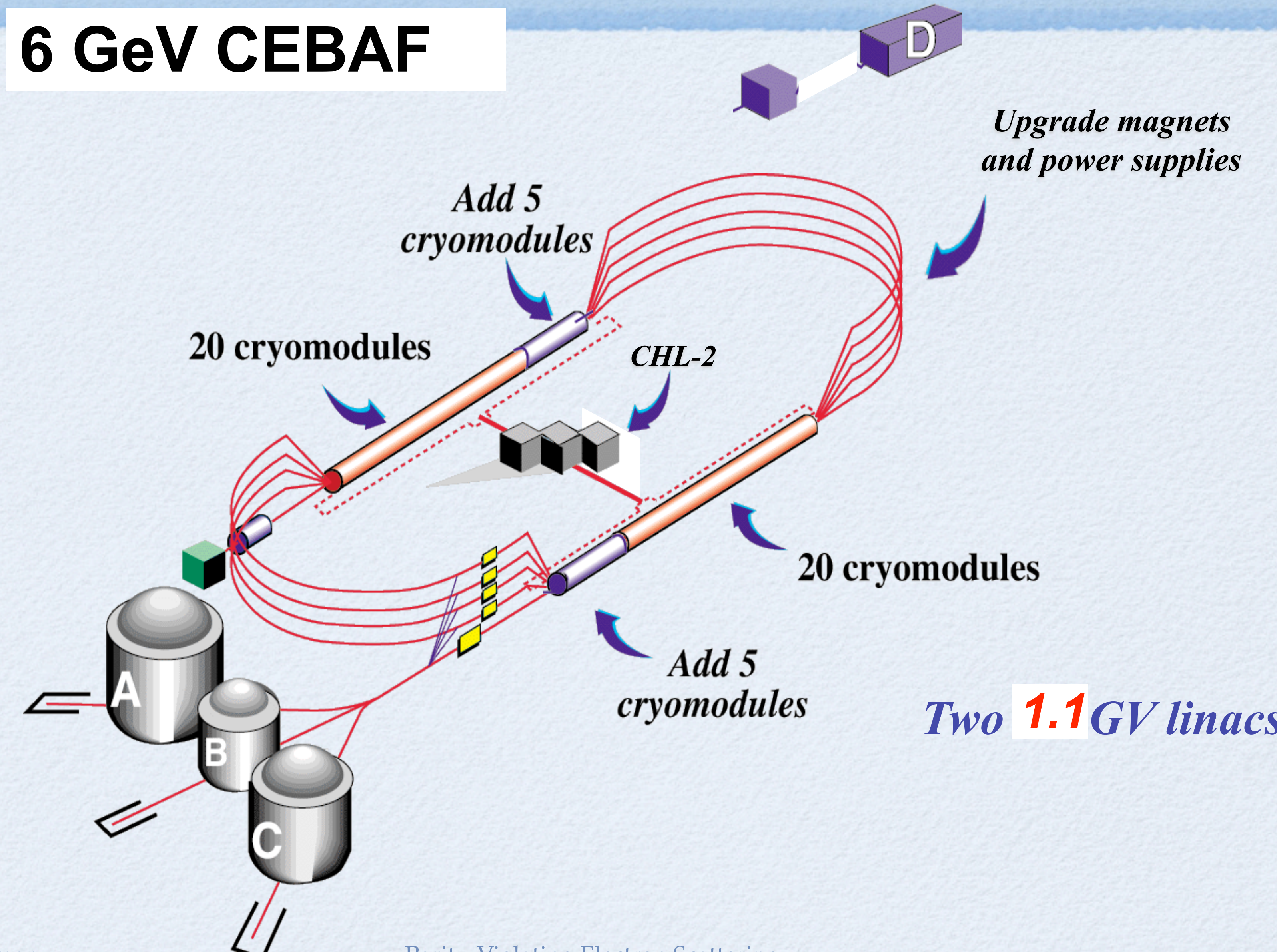

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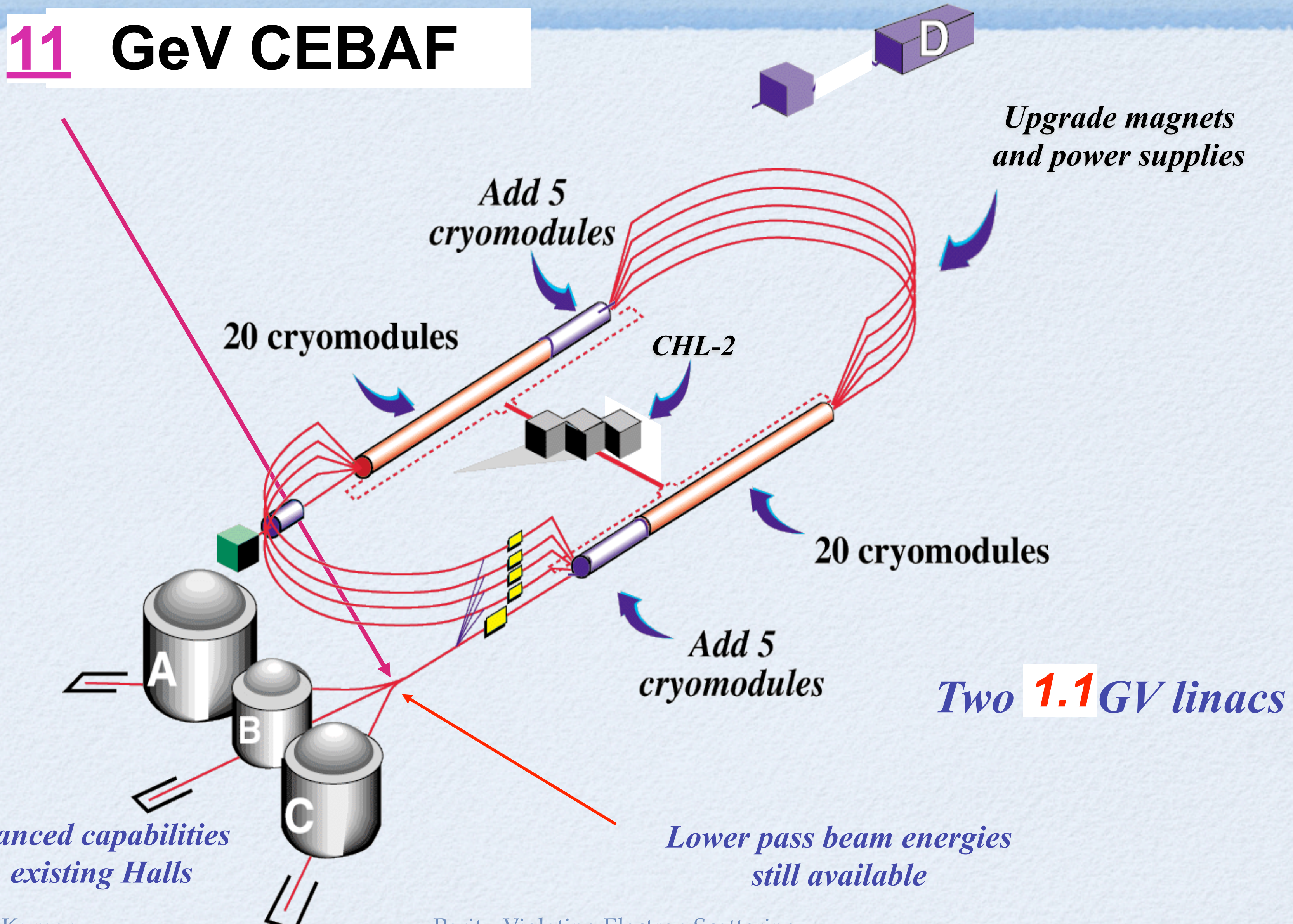

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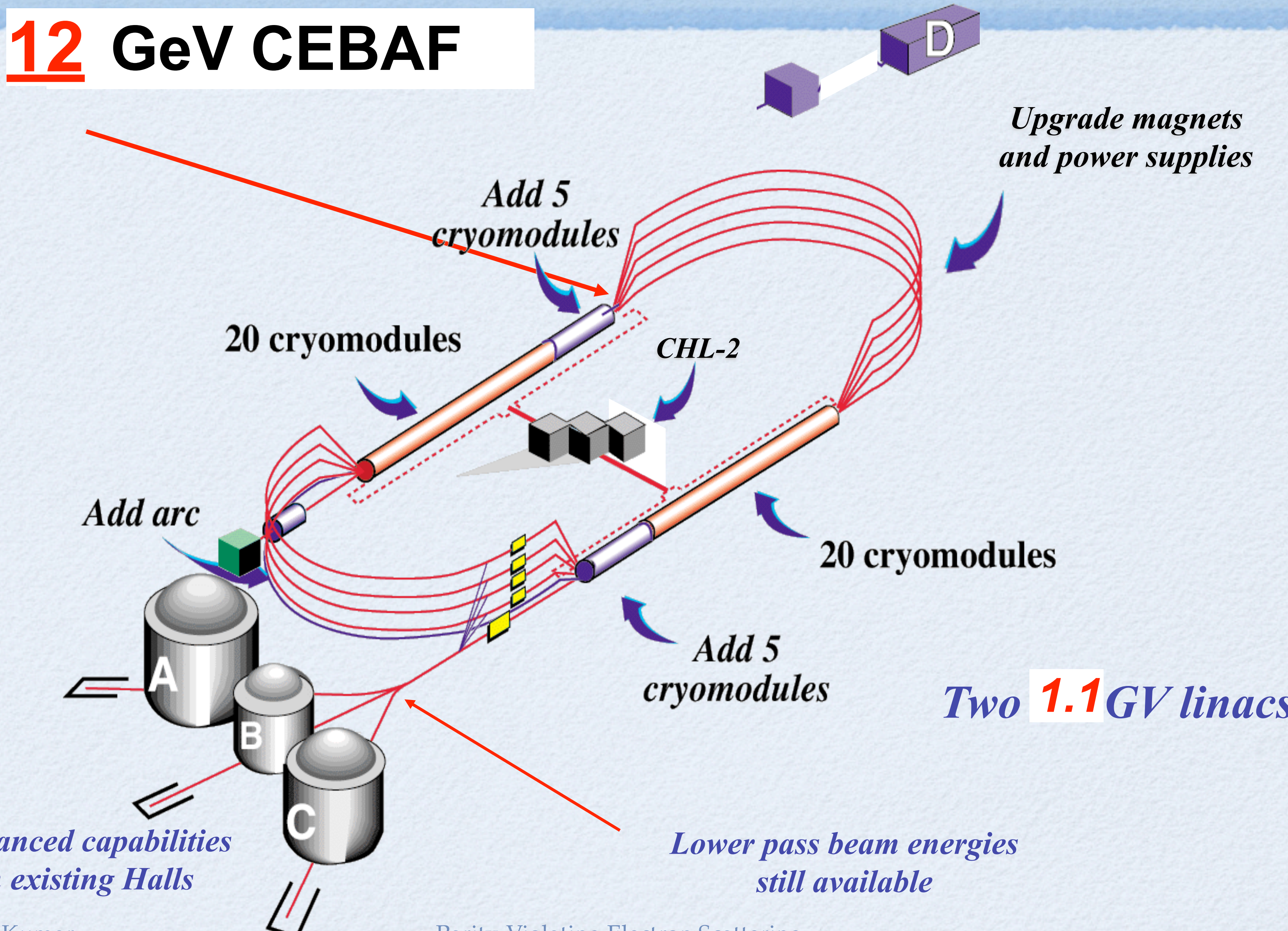

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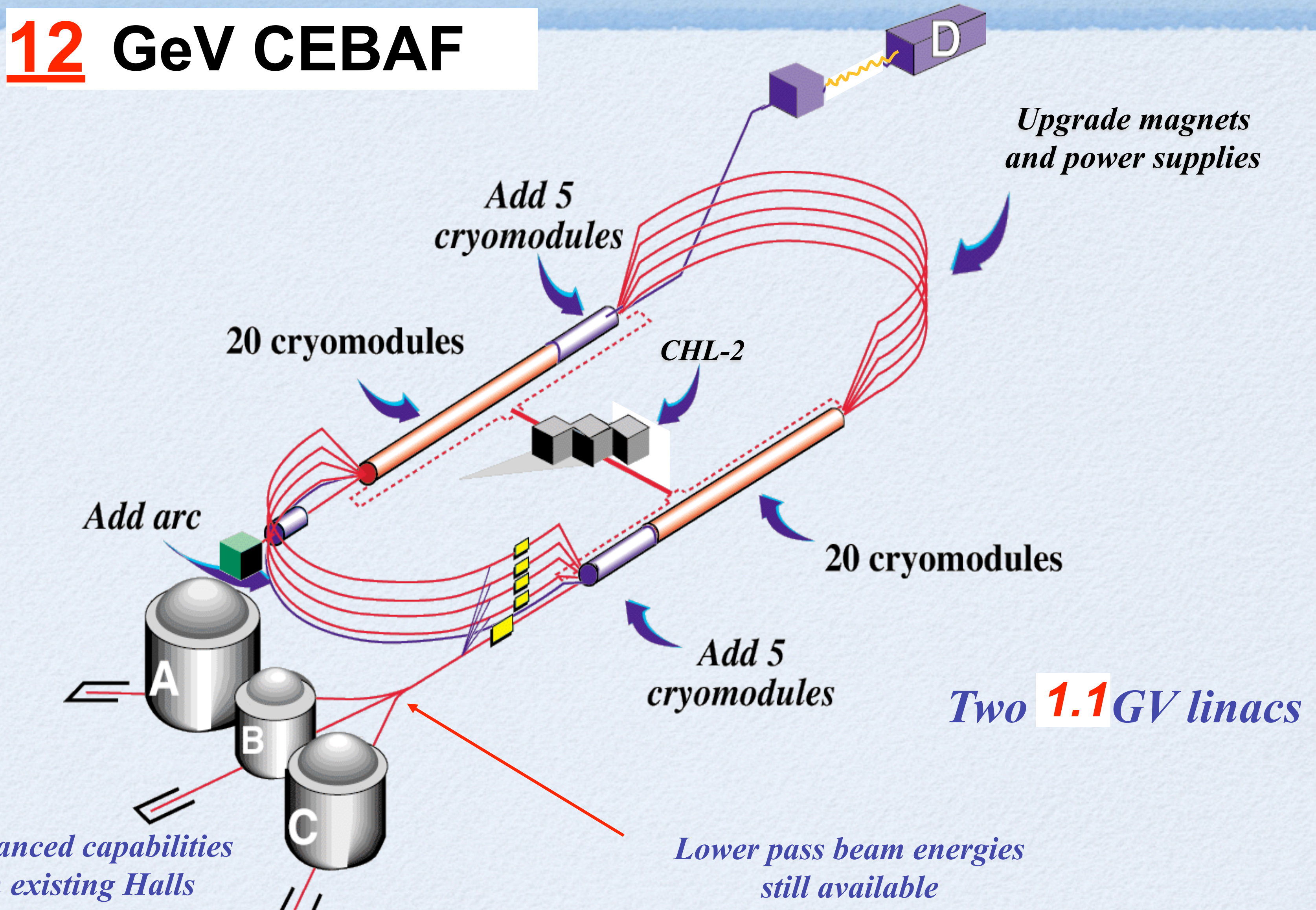

First ever model-independent constraint on neutron skin

PREX Plans

But ultimate goal is to get ~ 0.5 fm!

- *Plan to make necessary beamline modifications to ensure efficient running*
- *Propose to come back either just before or just after 12 GeV upgrade shutdown*
- *Thinking about new experiment on ^{48}Ca*

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^{48}Ca

- *Far from ^{208}Pb*
- *Compare to ^{40}Ca*
- *2 & 3 nucleon forces*
- *double-beta decay nucleus*

Statistical error at JLAB Hall A:
assuming 100μA, 5° for 30 days

	E	Rate	A_{pv}	R_n	$t(1\%)$
	(GeV)	MHZ	ppm	%	days
^{208}Pb	1.05	1700	0.72	0.66	**13**
	1.8	53	2.1		
^{120}Sn	1.2	1080	1.06	0.56	**9.4**
^{48}Ca	1.7	270	2.2	0.43	**5.5**
	2.1	21	2.8		

C. Horowitz and R. Michaels

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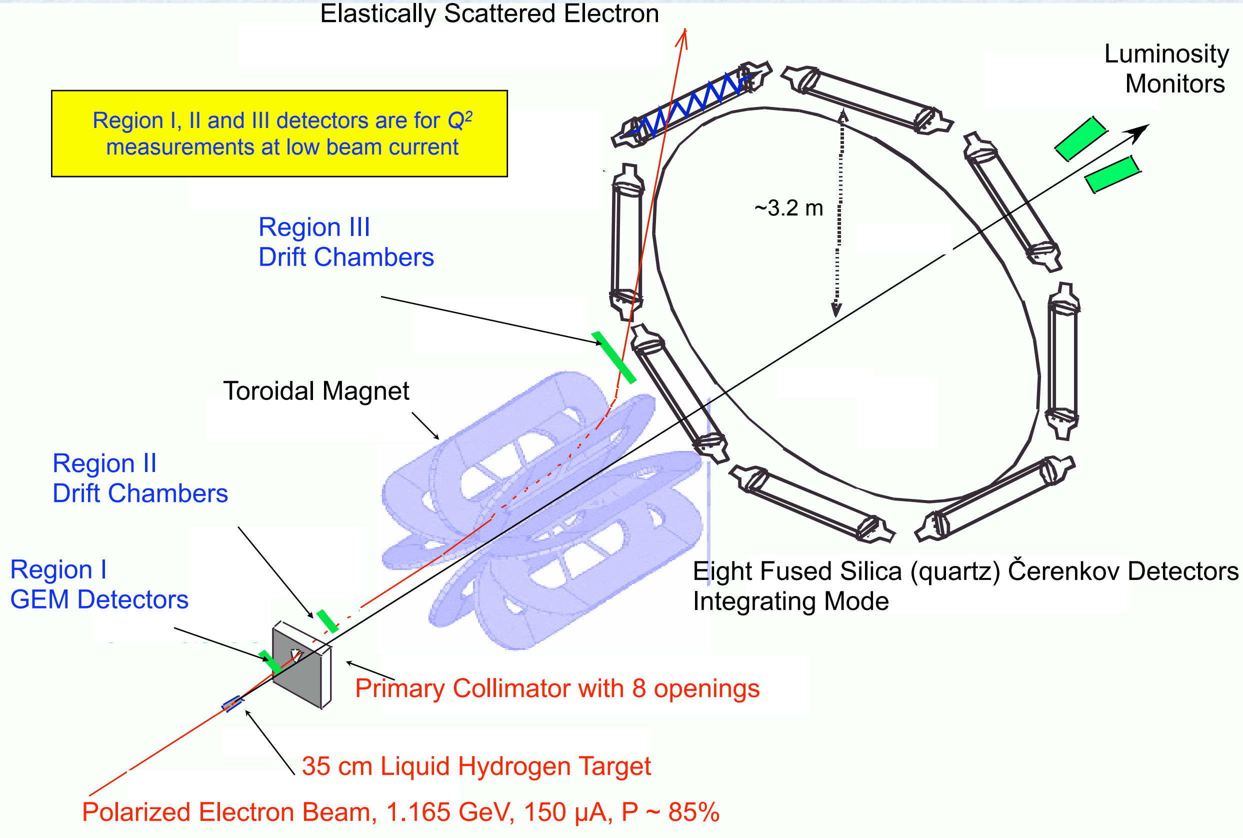
C. Horowitz and R. Michaels

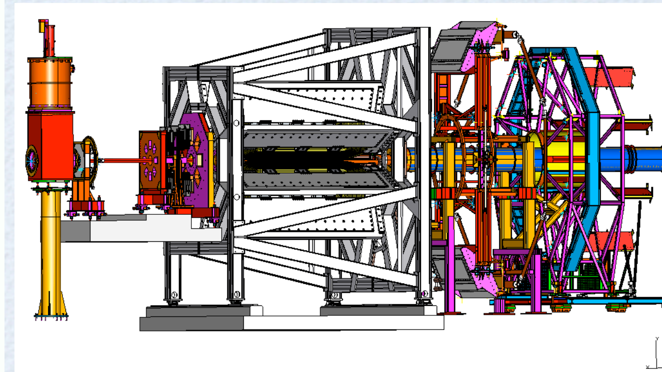
Robust, sub-1% neutron skin measurement will have lasting impact:

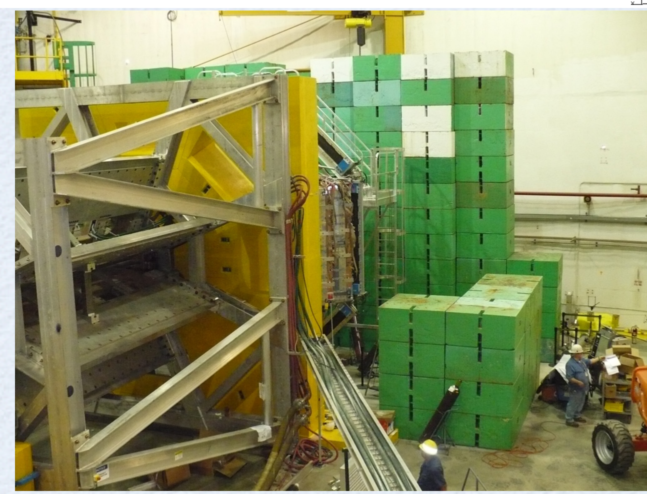
- many body nuclear theory
- constrain symmetry energy and its derivative @ nuclear density
- neutron star physics

Qweak @ Jefferson Lab

Precision Measurement of the Proton's Weak Charge







- Design and construction over past several years
- Successful installation and commissioning
- Data ~ 2010 thru mid-2012
- 25% of production data accumulated

New, complementary constraints on lepton-quark interactions at the TeV scale

Systematic Errors

source of error	% error
absolute value of Q^2	0.5
beam second order	0.4
longitudinal beam polarization	0.4
inelastic e-p scattering	0.4
elastic e-p scattering	0.3
beam first order	0.3
pions and muons	0.3
transverse polarization	0.2
photons and neutrons	0.1
Total	1.0

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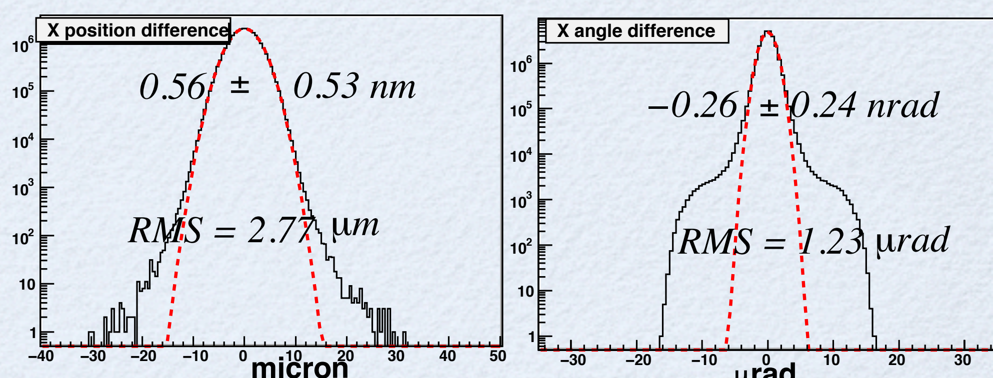
- I order beam helicity correlations
  - position to 0.5 nm, angle to 0.05 nrad
  - active intensity, position and angle feedback
- II order beam helicity correlations
  - control laser spotsize fluctuations to 10^{-4}
  - slow flips with Wien filter and g-2 energy flip

HAPPEXII



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pions and muons	0.3
transverse polarization	0.2
photons and neutrons	0.1
Total	1.0

- longitudinal beam polarization
  - strive for redundant, continuous monitoring
  - pursue both Compton and Atomic Hydrogen
- transverse beam polarization
  - kinematic separation allows online monitoring
  - slow feedback using Wien filter
- Absolute value of Q^2
  - dedicated tracking and scanning detectors
  - experience with HAPPEXII & Qweak
  - easier than elastic e-p scattering

- I order beam helicity correlations
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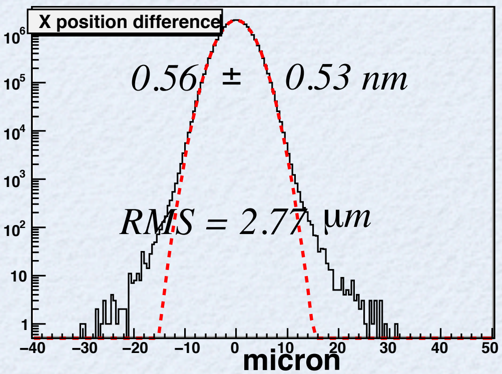
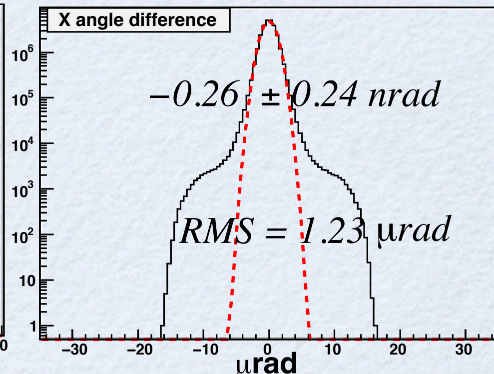
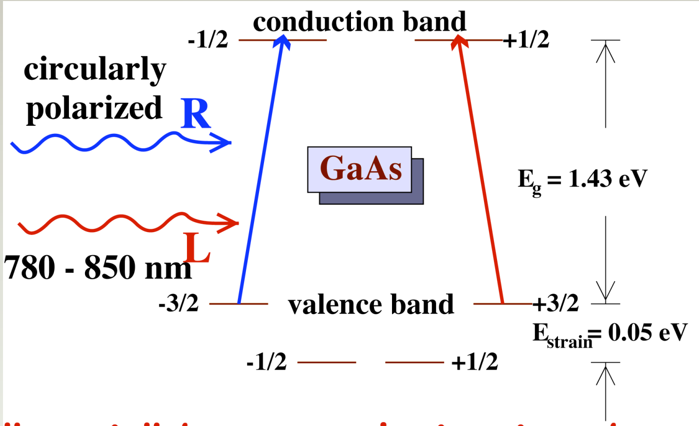
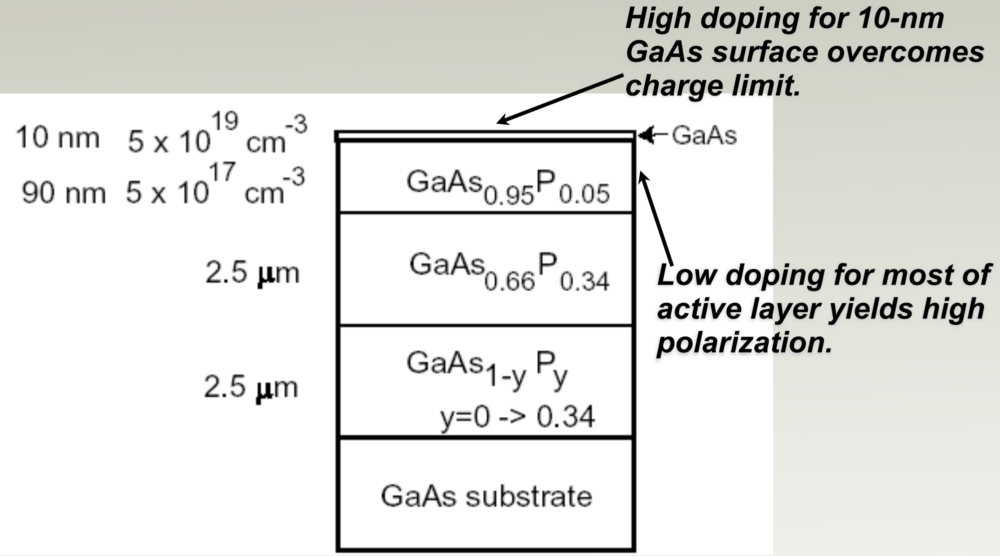




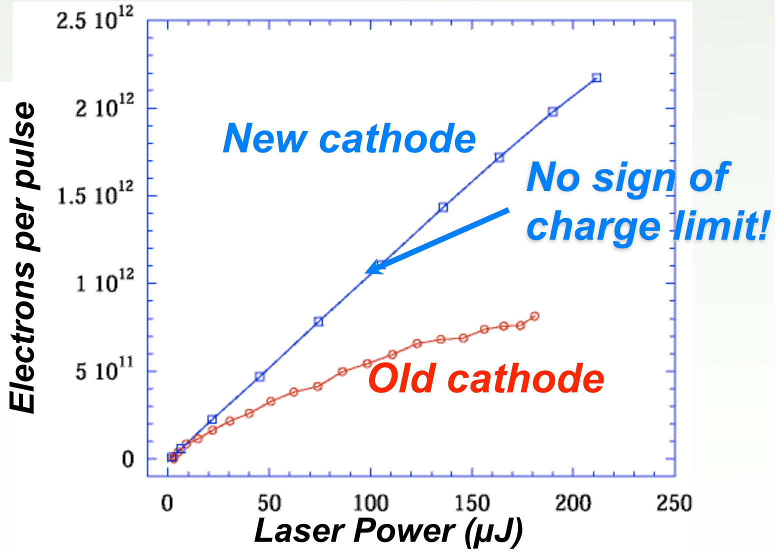
Polarized Beam



"strain" boosts polarization, but introduces anisotropy in response



Parameter	E158	NLC-500
Charge/Train	6×10^{11}	14.3×10^{11}
Train Length	270ns	260ns
Bunch spacing	0.3ns	1.4ns
Rep Rate	120Hz	120Hz
Beam Energy	45 GeV	250 GeV
e^- Polarization	80%	80%



E158 Collaboration & Chronology

Parity-Violating Left-Right Asymmetry In Fixed Target Møller Scattering

At the Stanford Linear Accelerator Center

Goal: error small enough to probe TeV scale physics

E158 Collaboration

- **Berkeley**
- **Caltech**
- **Jefferson Lab**
- **Princeton**
- **Saclay**
- **SLAC**
- **Smith**
- **Syracuse**
- **UMass**
- **Virginia**

8 Ph.D. Students

60 physicists

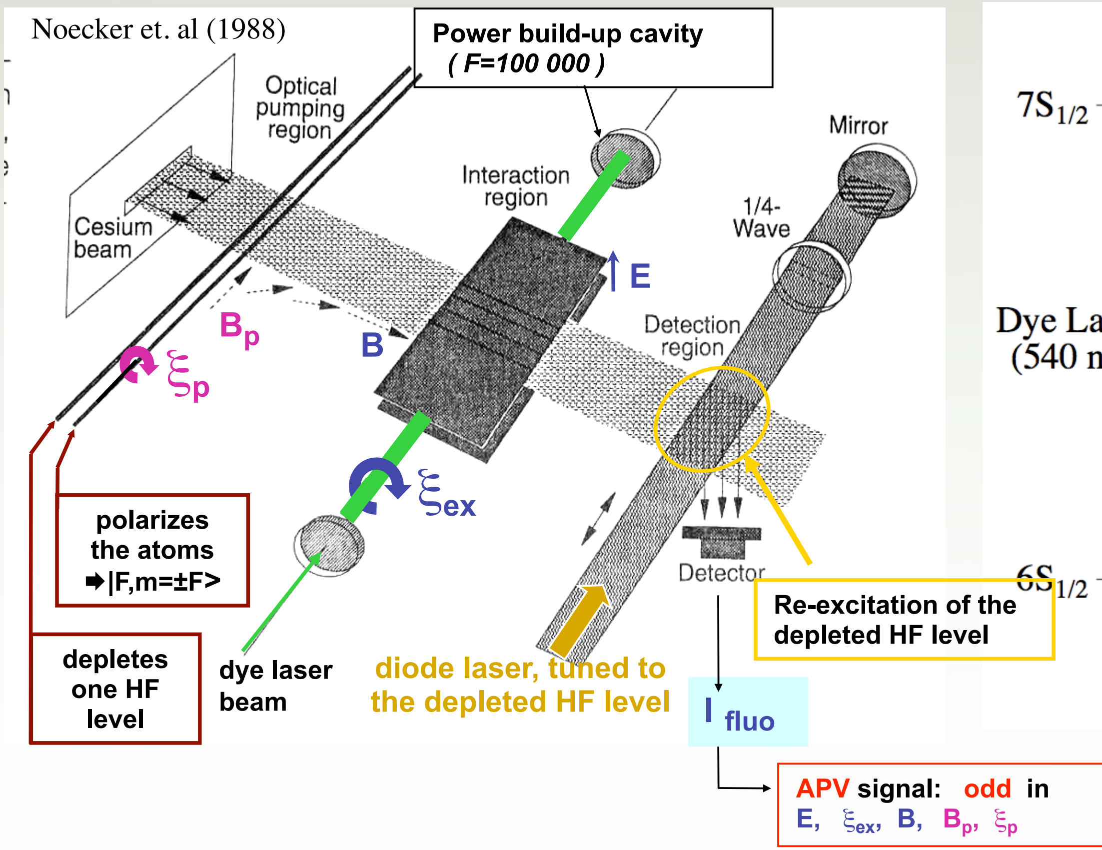
E158 Chronology

Feb 96: Workshop at Princeton
Sep 97: SLAC EPAC approval
Mar 98: First Laboratory Review
1999: Design and Beam tests
2000: Funding and construction
2001: Engineering run
2002-2003: Physics
2004: First PRL
2005: PRL on full statistics

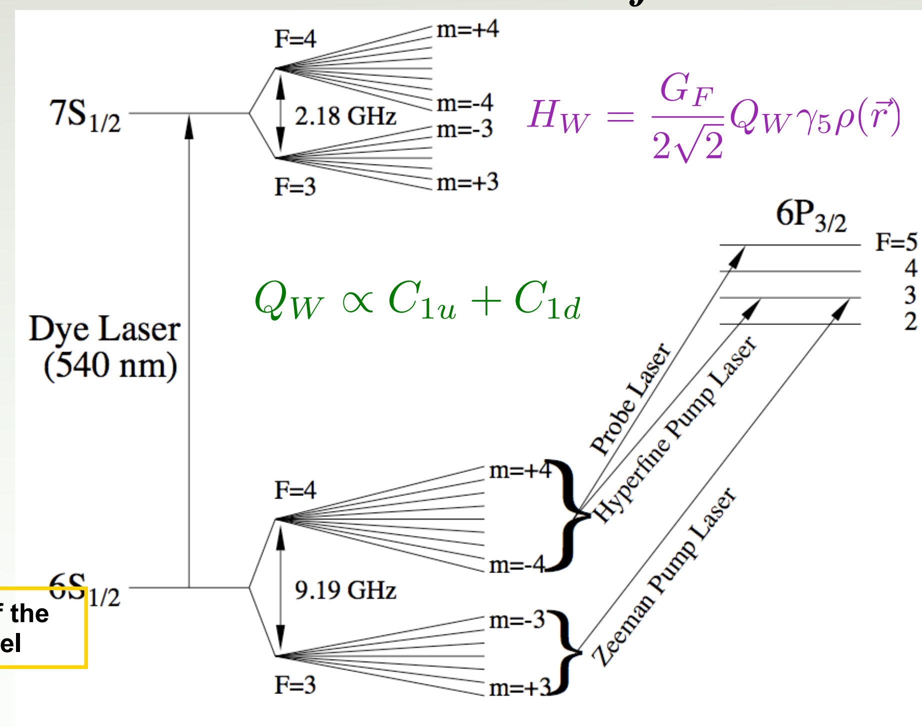
Atomic Parity Violation

- *6S → 7S transition in ^{133}Cs is forbidden within QED*
- *Parity Violation introduces small opposite parity admixtures*
- *Induce an E1 Stark transition, measure E1-PV interference*
- *5 sign reversals to isolate APV signal and suppress systematics*
- *Signal is ~ 6 ppm, measured to 40 ppb*

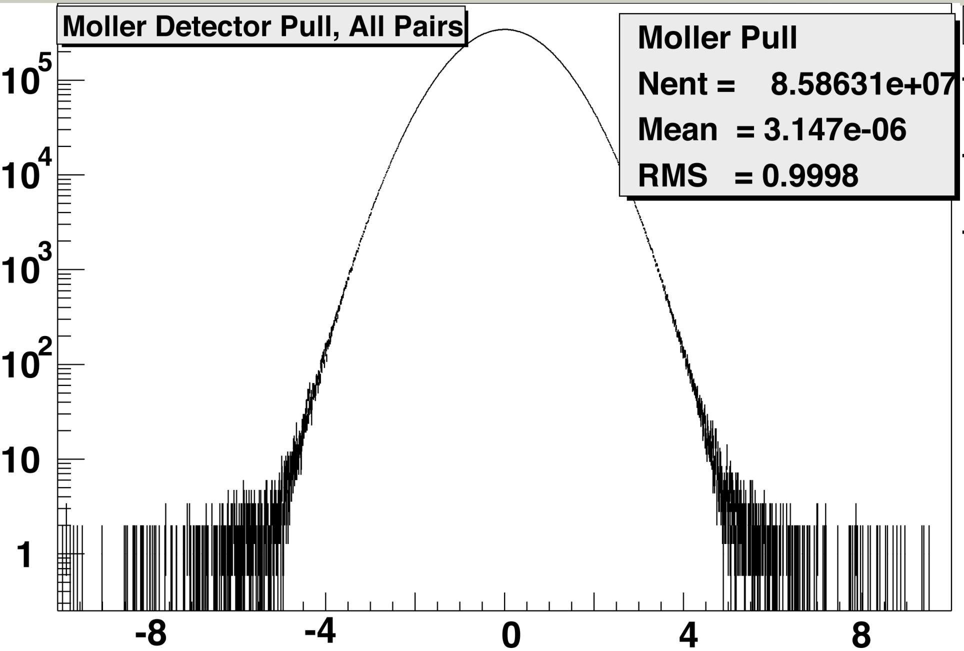
Boulder Experiment

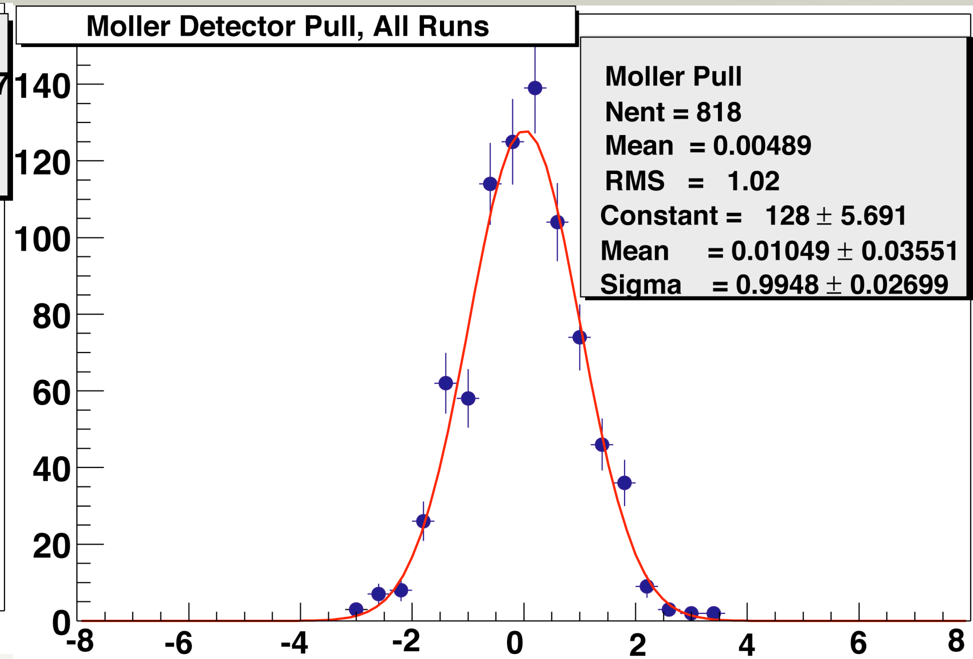


Partial Level Structure of Cesium



Raw Asymmetry Statistics





$$\frac{A_i - \langle \overline{A} \rangle}{\sigma_i}$$

$\sigma_i \approx 200\ ppm$

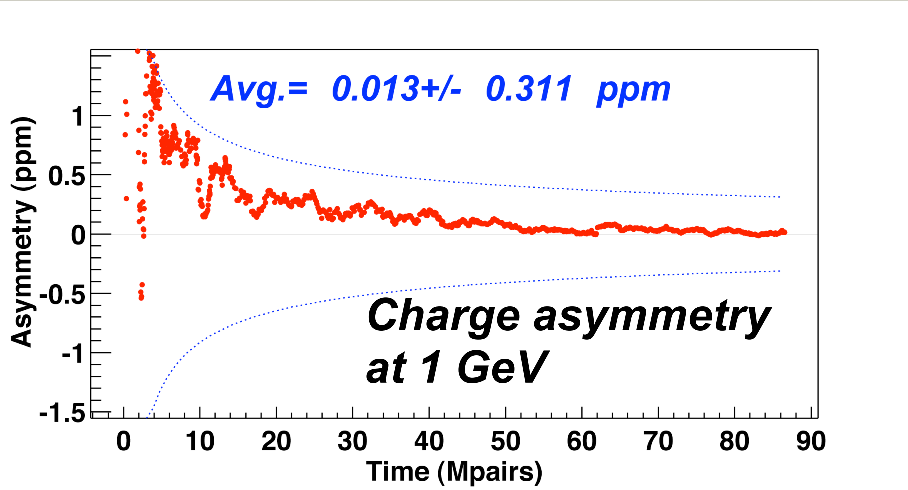
$N = 85\ Million$

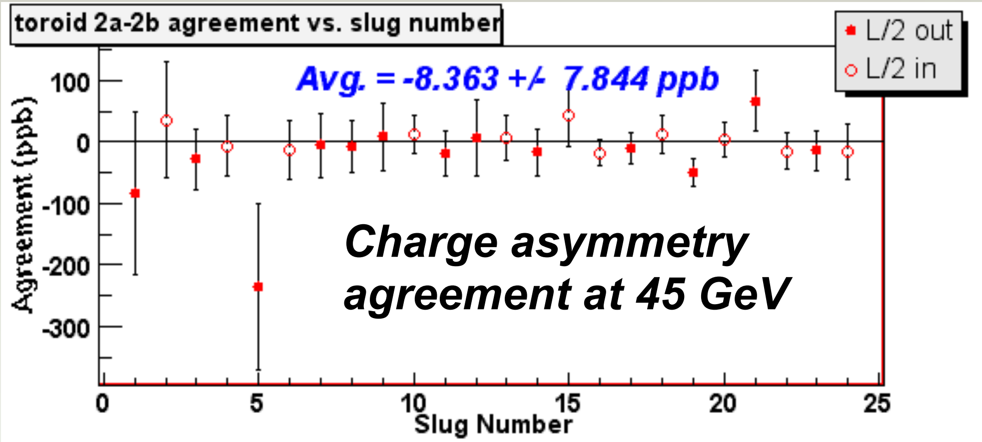
$$\frac{A_i - \langle \overline{A} \rangle}{\sigma_i}$$

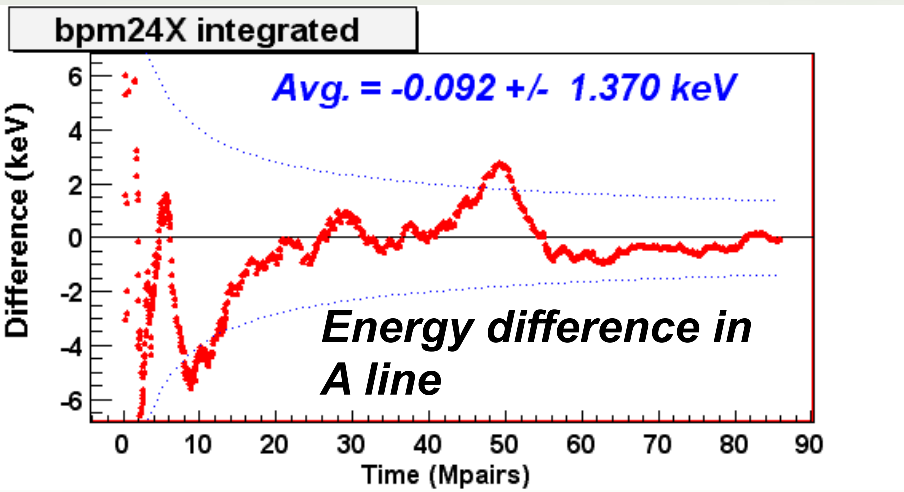
$\sigma_i \approx 600\ ppb$

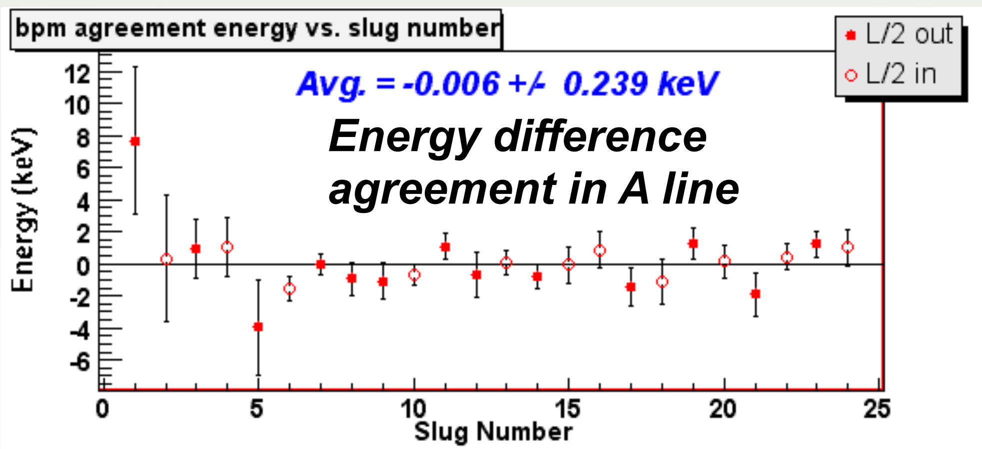
$N = 818$

Beam Asymmetries





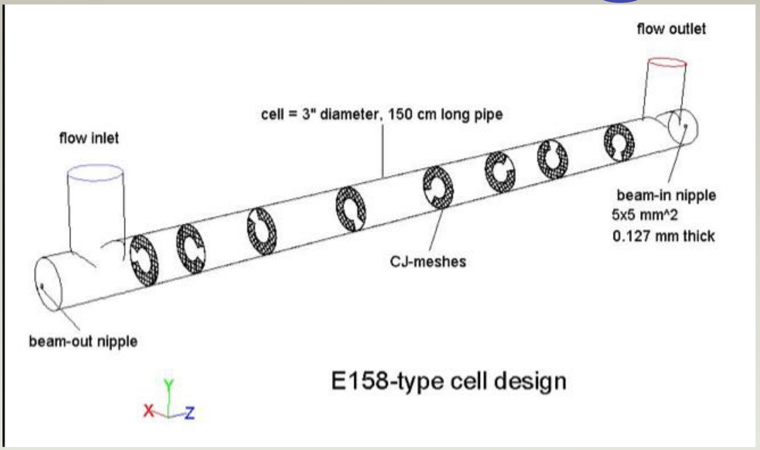




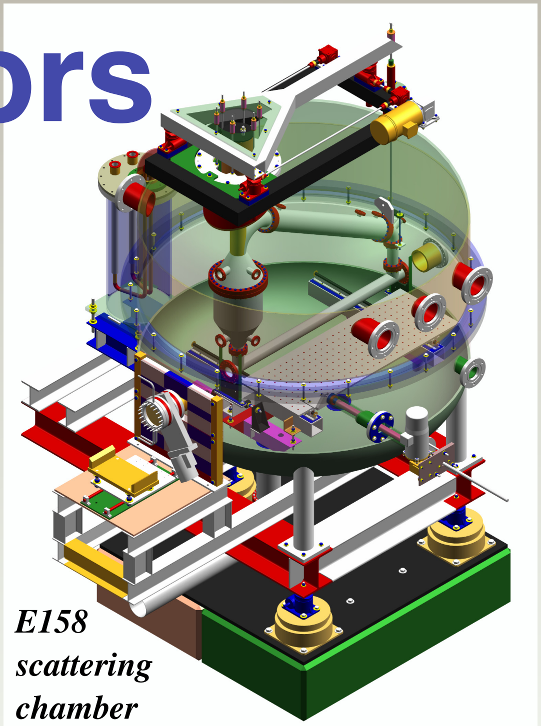
Position differences < 20 nm

Position agreement ~ 1 nm

Target & Detectors

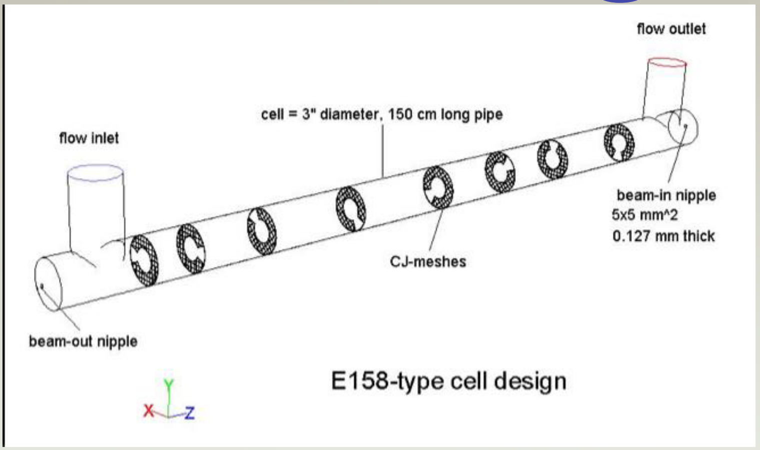


parameter	value
length	*150 cm*
thickness	*10.7 gm/cm^2*
X_0	*17.5%*
p,T	*35 psia, 20K*
power	*5000 W*

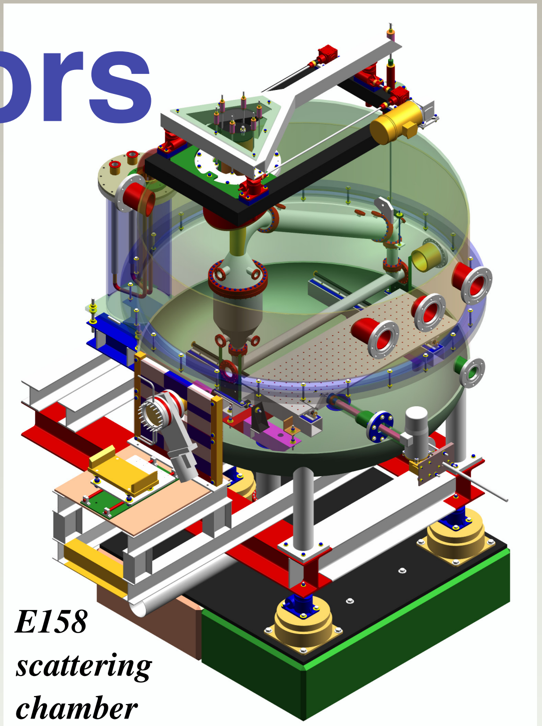


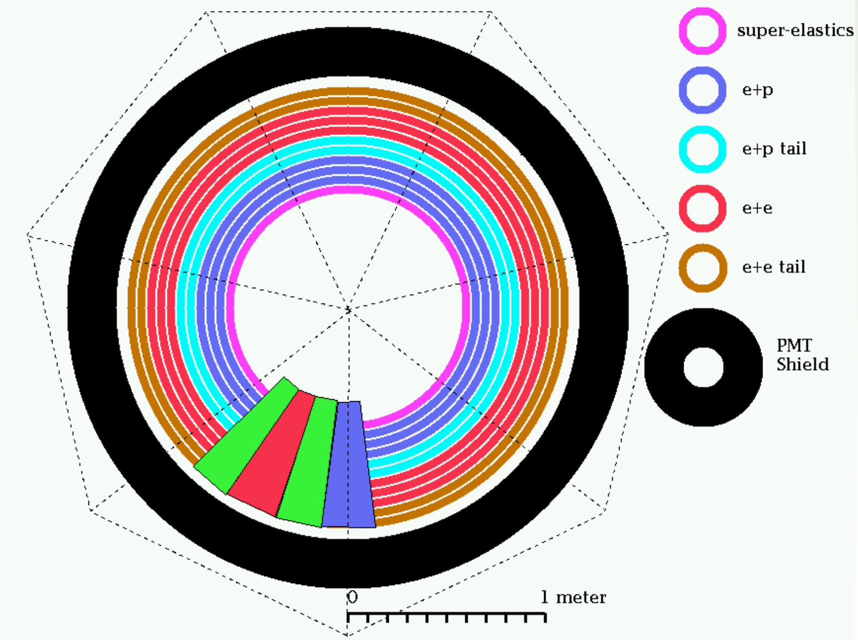
E158 scattering chamber

Target & Detectors

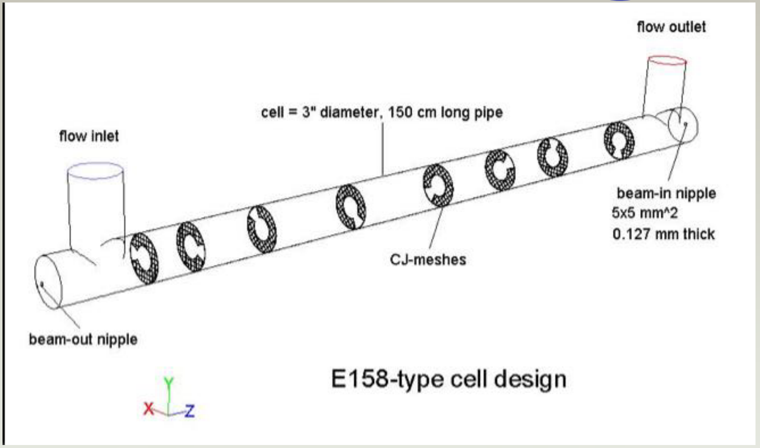


parameter	value
length	*150 cm*
thickness	*10.7 gm/cm²*
X_0	*17.5%*
p,T	*35 psia, 20K*
power	*5000 W*

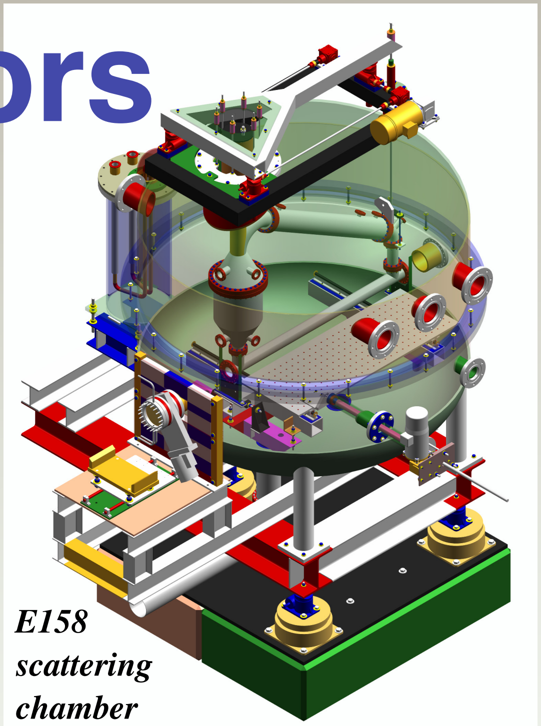

E158 scattering chamber



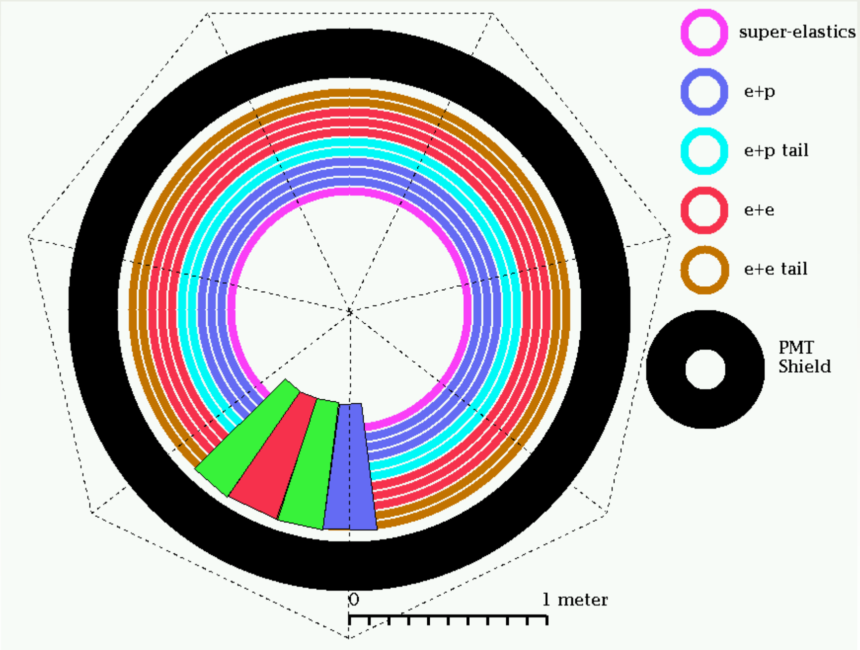
Target & Detectors

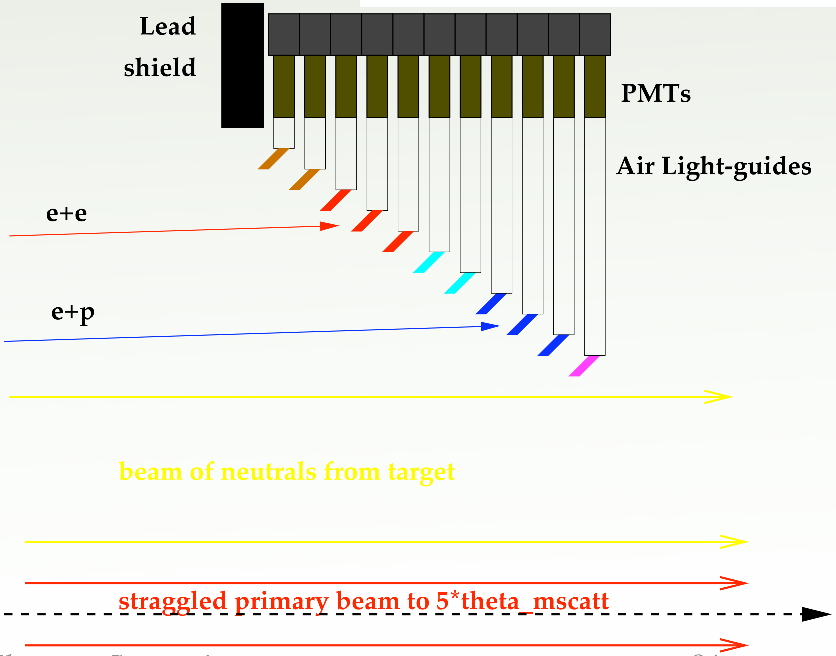


parameter	value
length	*150 cm*
thickness	*10.7 gm/cm²*
X_0	*17.5%*
p,T	*35 psia, 20K*
power	*5000 W*

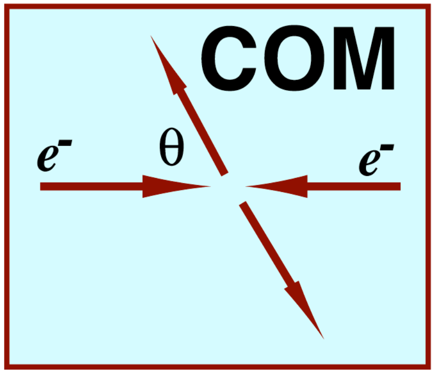


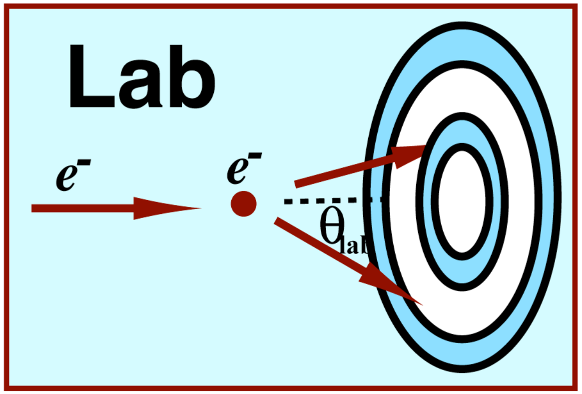
E158 scattering chamber

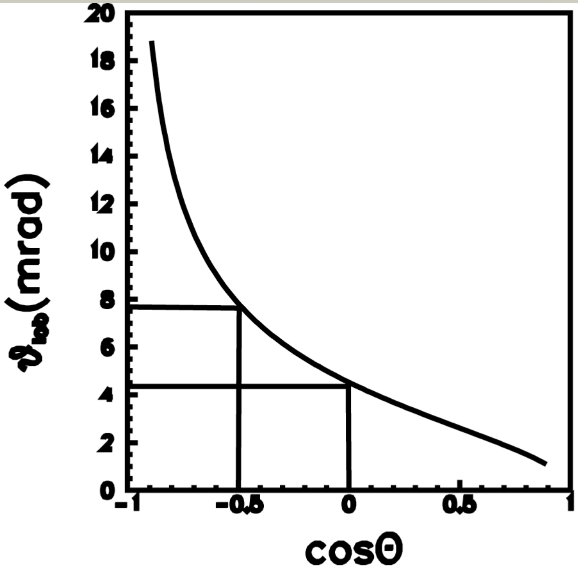




Kinematics

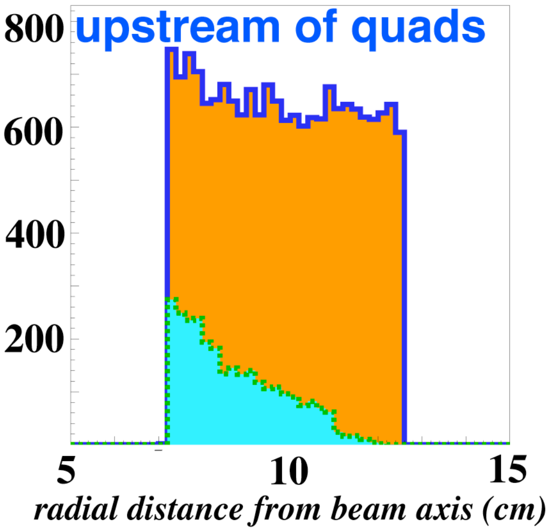


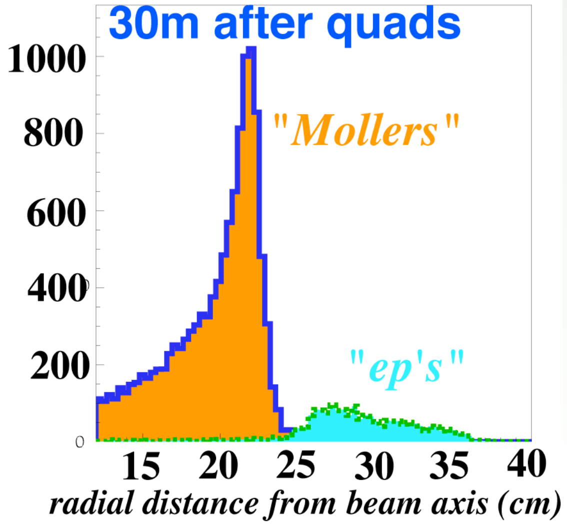




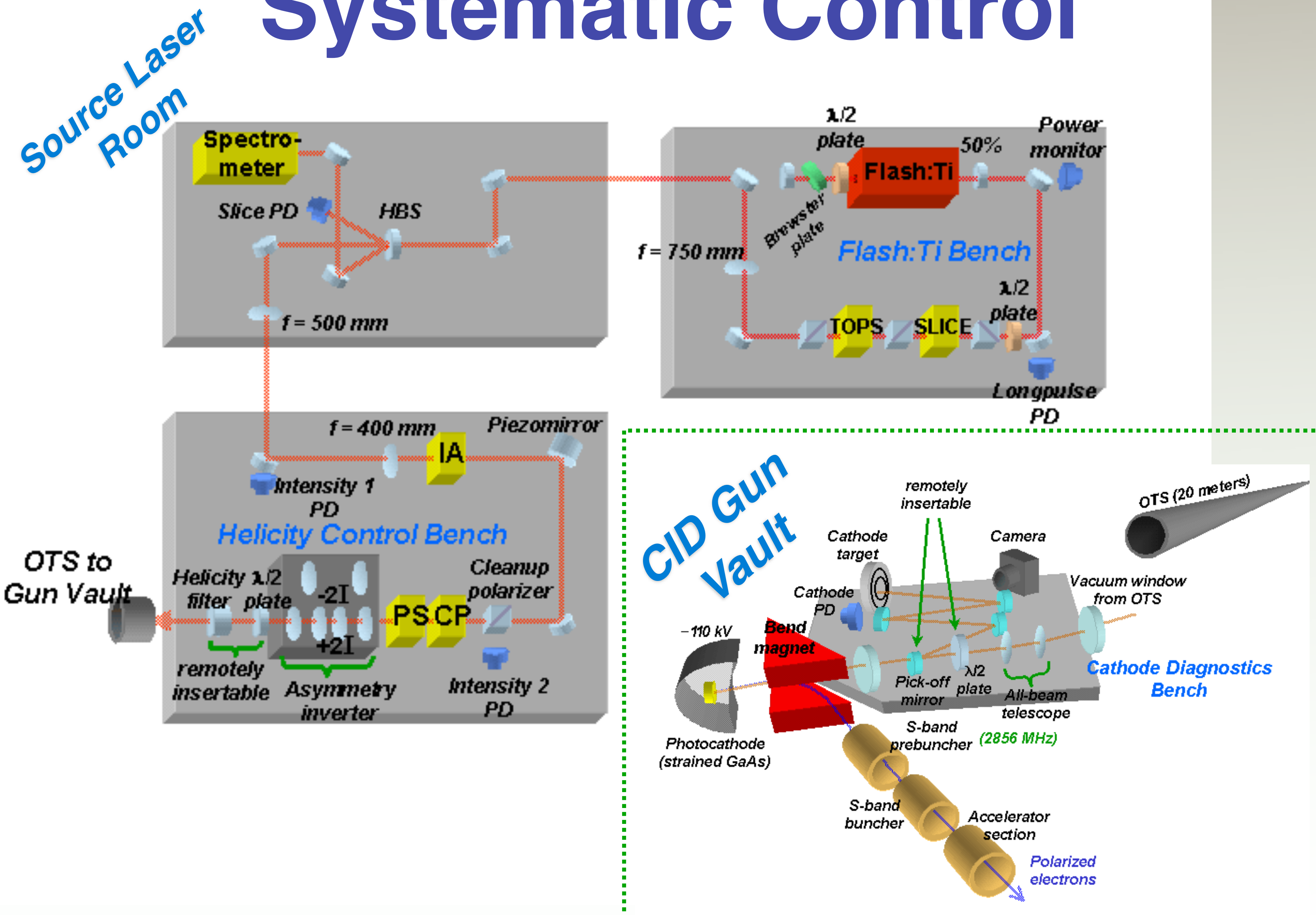
Quadrupole Quadruplet

- *primary & scattered electrons enclosed in quadrupoles*
- *Mollers (e-e) focused, Motts (e-p) defocused*
- *full range of azimuth*





Systematic Control



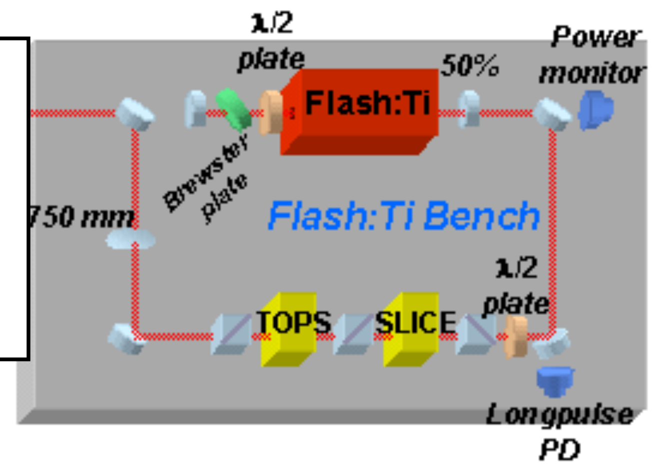
Systematic Control

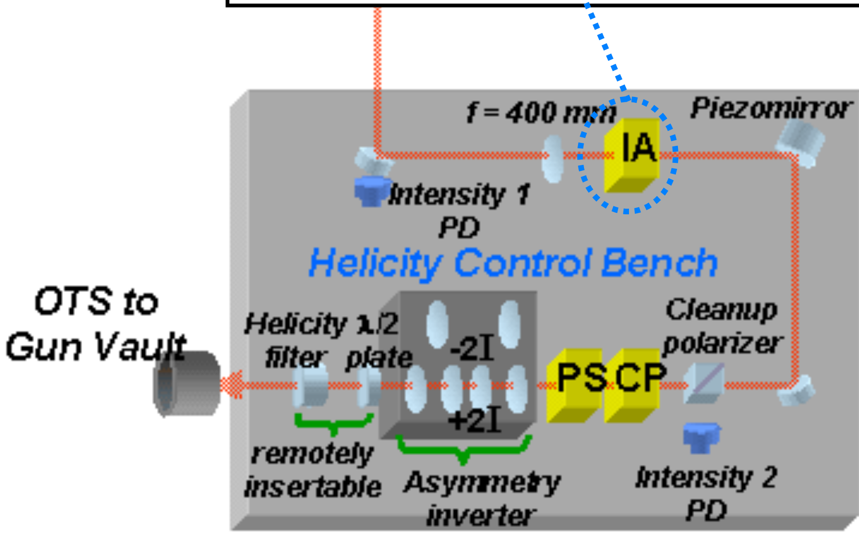
Source Laser Room

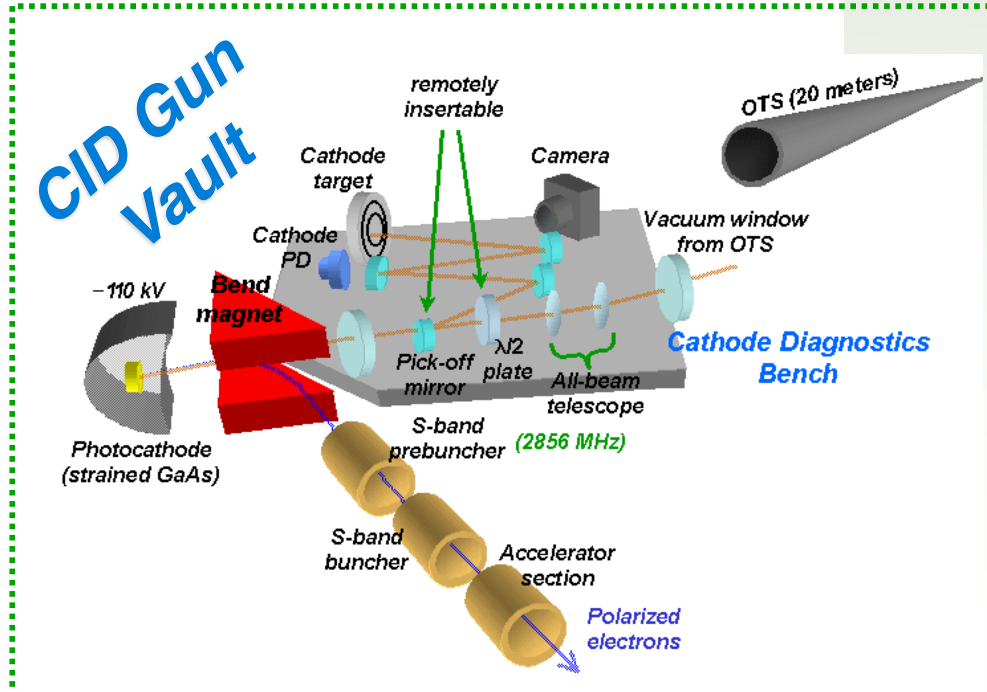
IA Feedback Loop

IA cell applies a helicity-correlated phase shift to the beam.

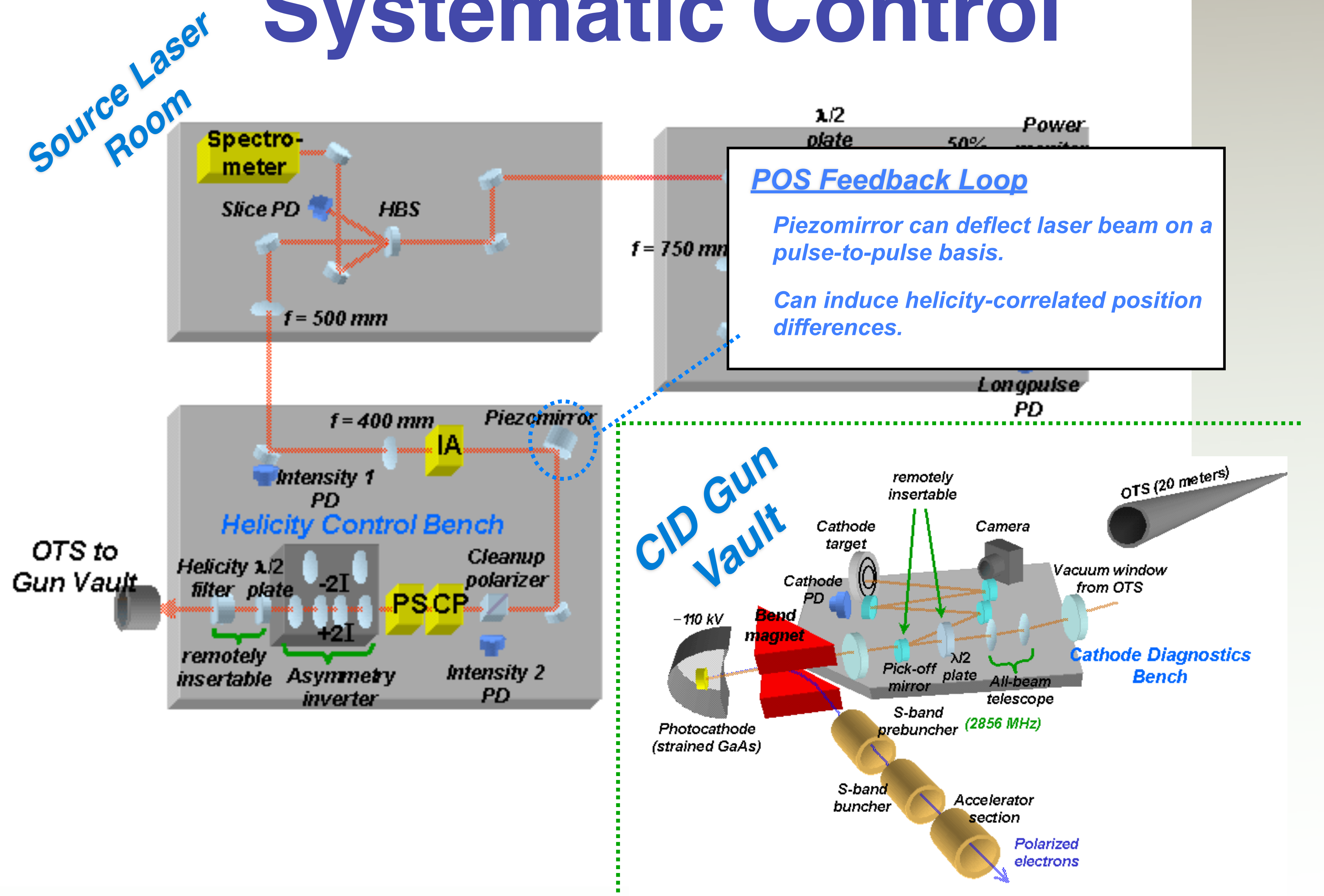
The cleanup polarizer transforms this into intensity asymmetry.







Systematic Control

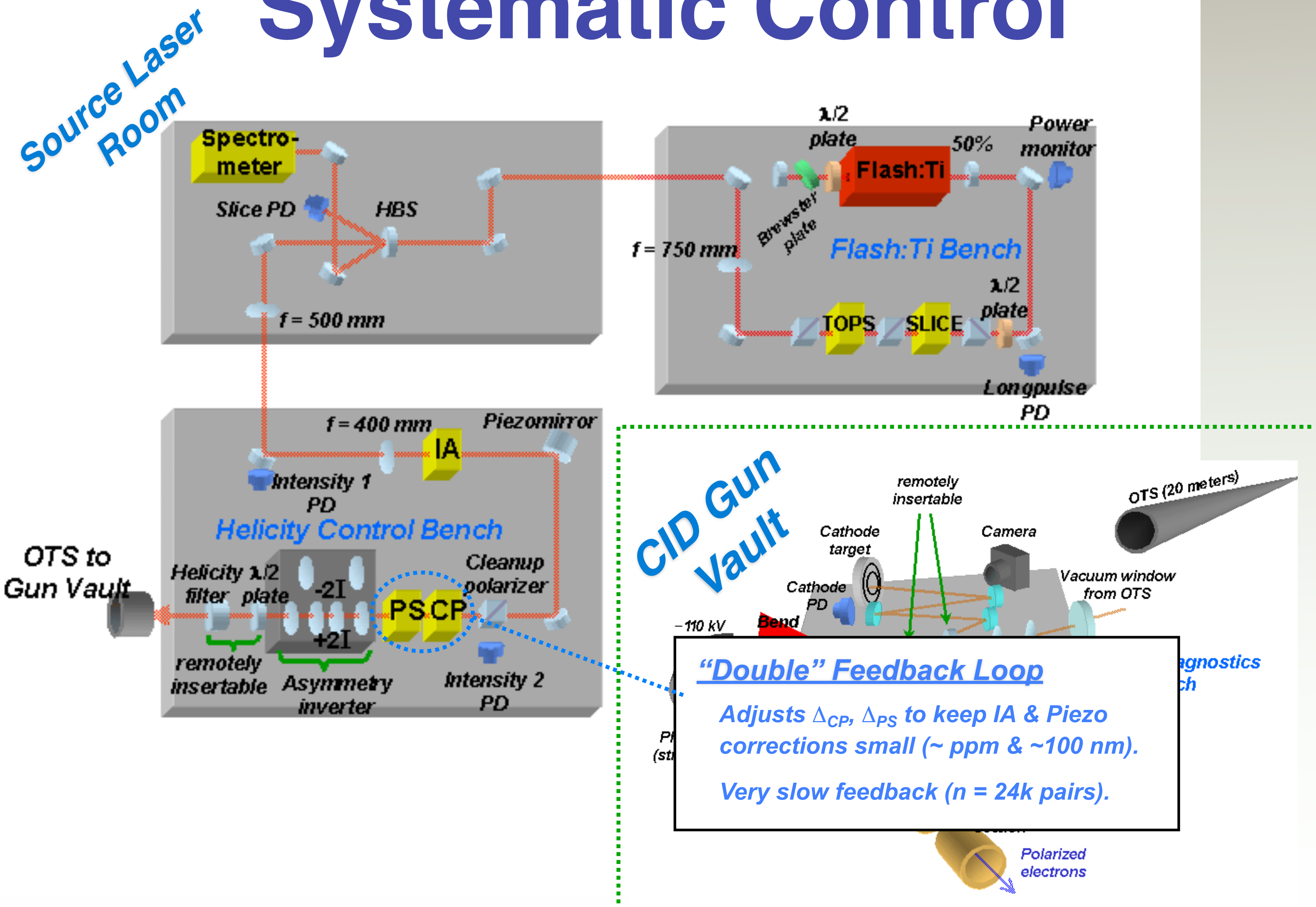


POS Feedback Loop

Piezomirror can deflect laser beam on a pulse-to-pulse basis.

Can induce helicity-correlated position differences.

Systematic Control

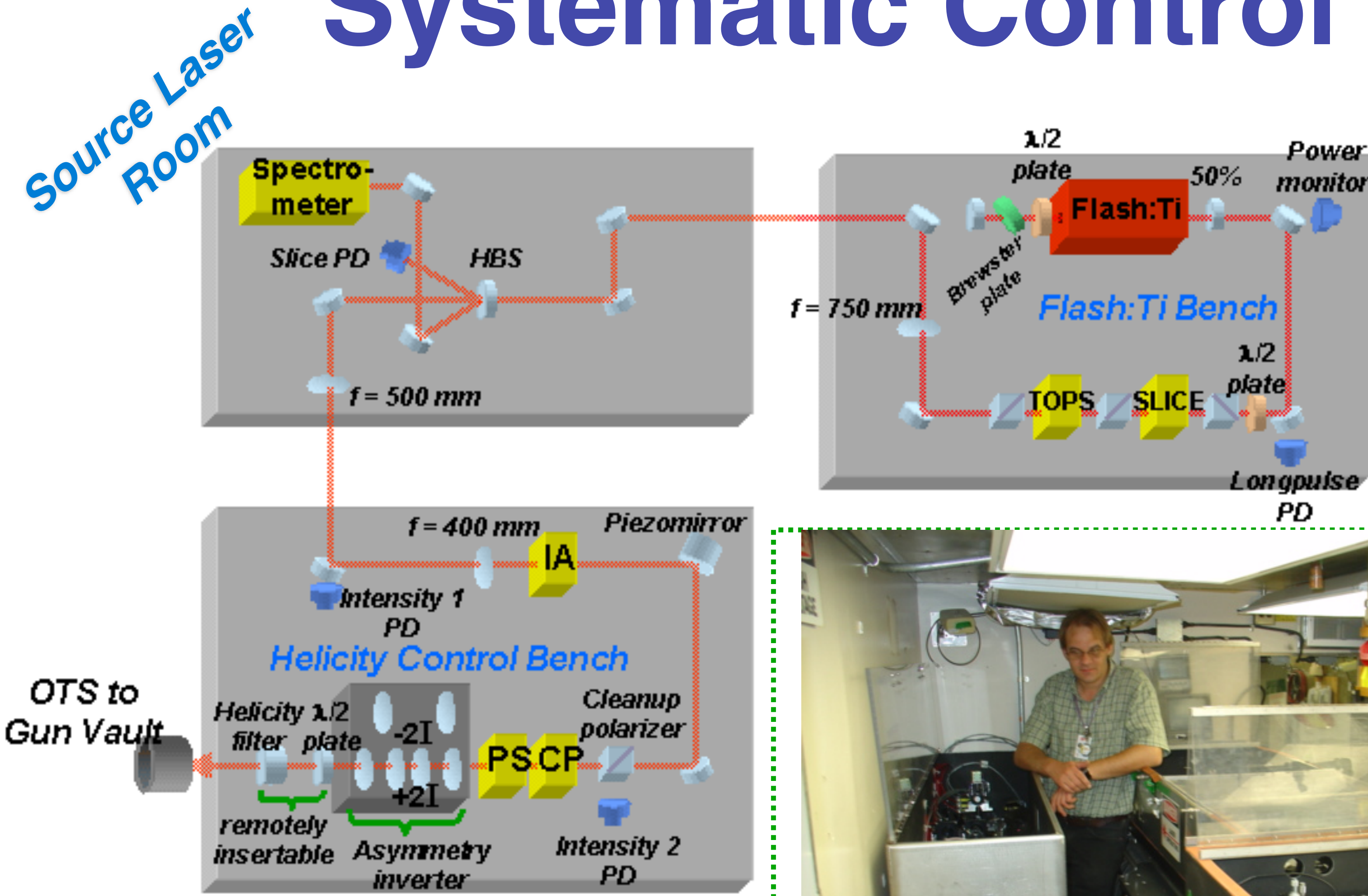


"Double" Feedback Loop

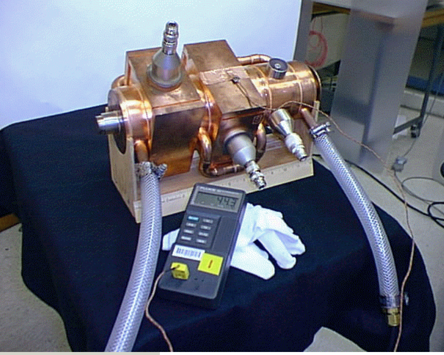
Adjusts Δ_{CP}, Δ_{PS} to keep IA & Piezo corrections small (~ ppm & ~100 nm).

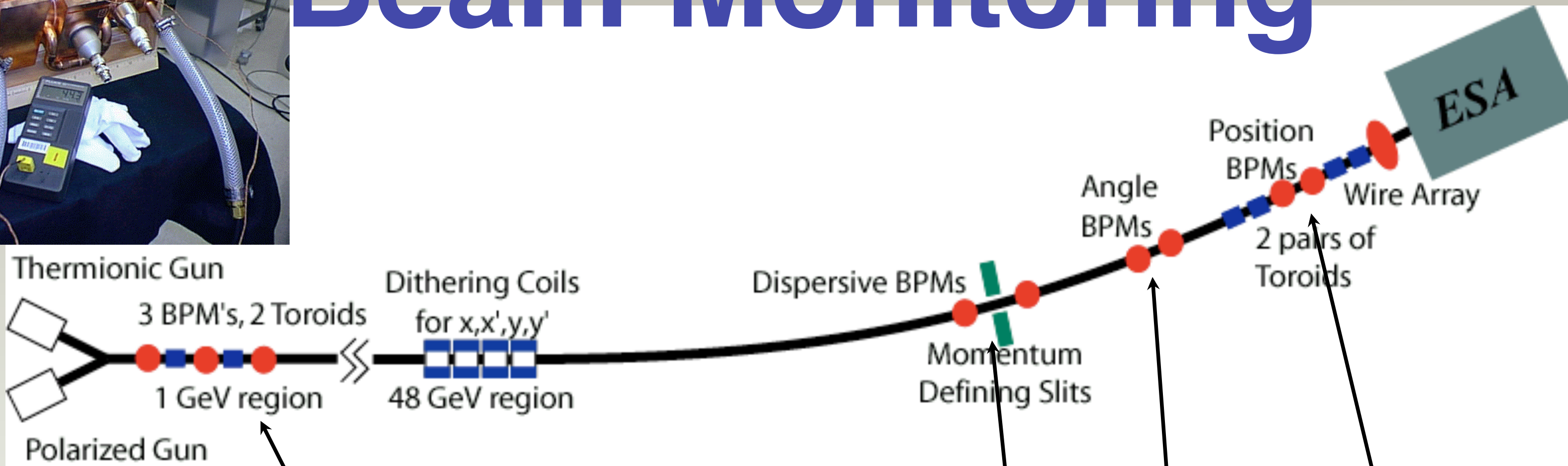
Very slow feedback (n = 24k pairs).

Systematic Control



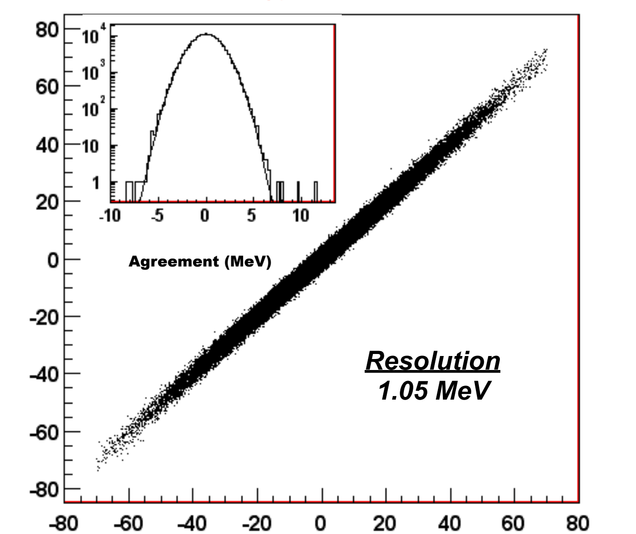
Beam Monitoring



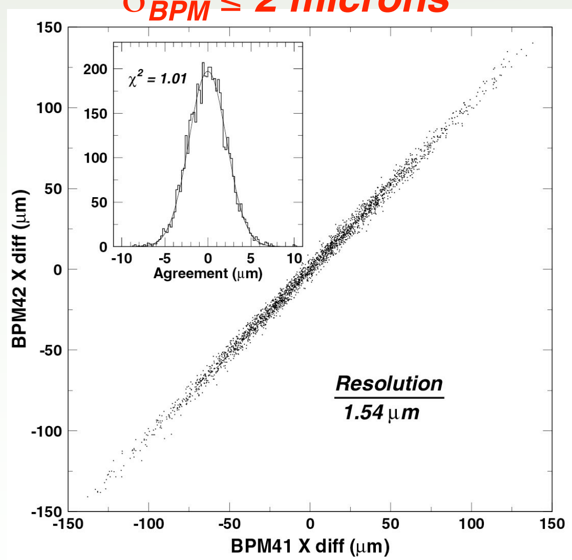


Event by event monitoring at 1 GeV and 45 GeV

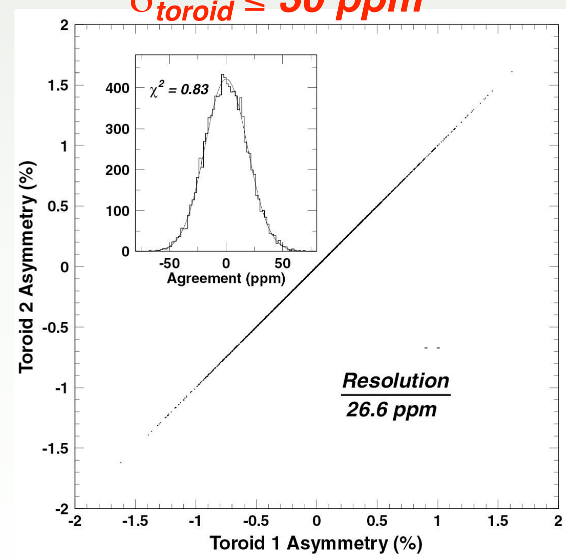
$\sigma_{energy} \leq$ ***1 MeV***



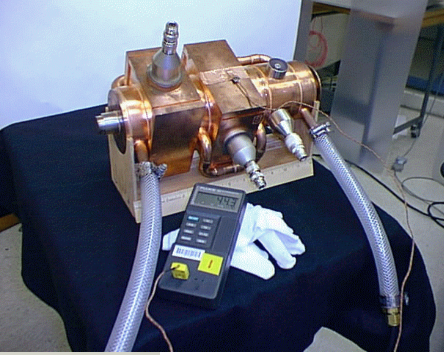
$\sigma_{BPM} \leq$ ***2 microns***

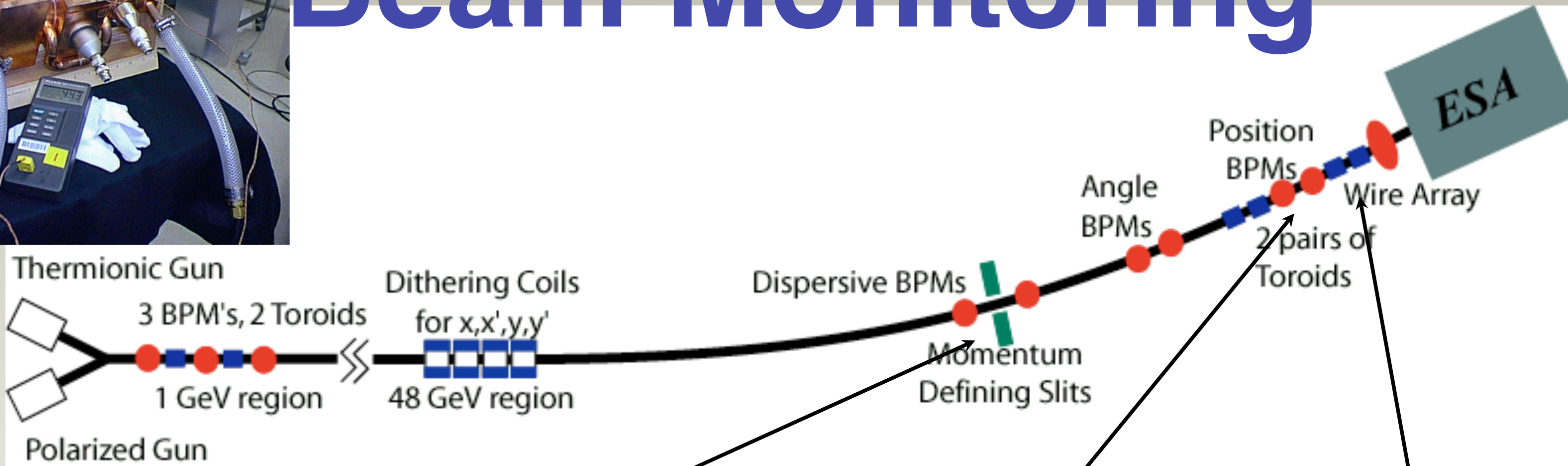


$\sigma_{toroid} \leq$ ***30 ppm***

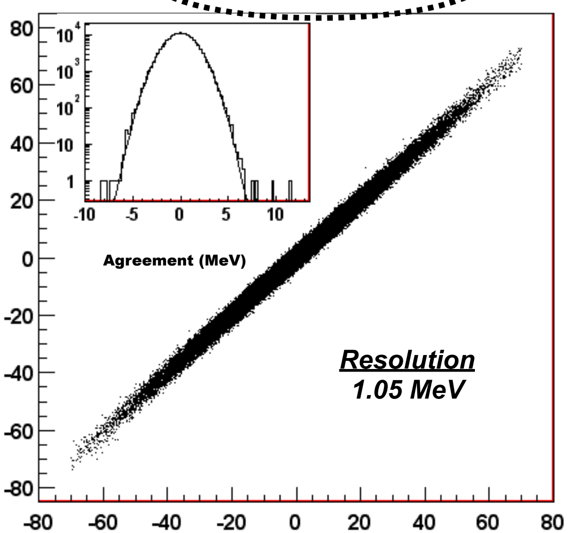


Beam Monitoring

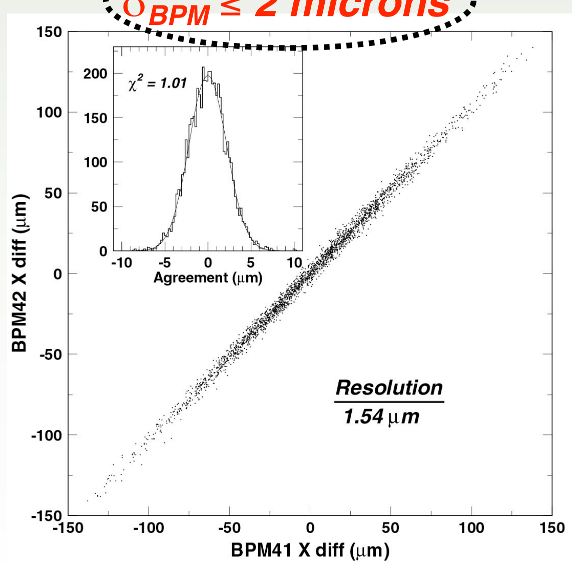




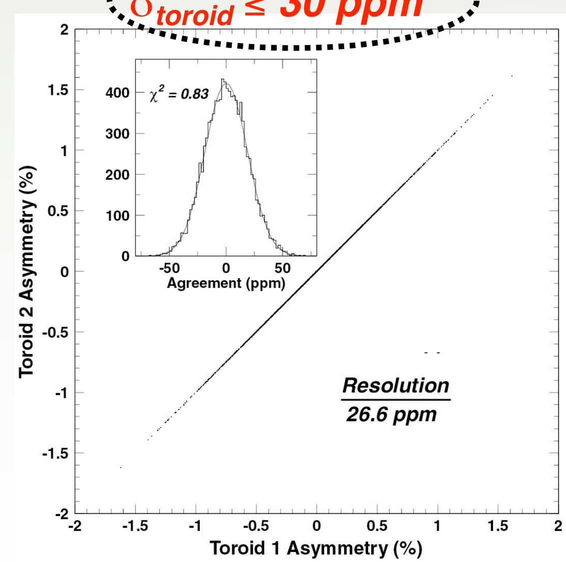
$\sigma_{energy} \leq$ 1 MeV



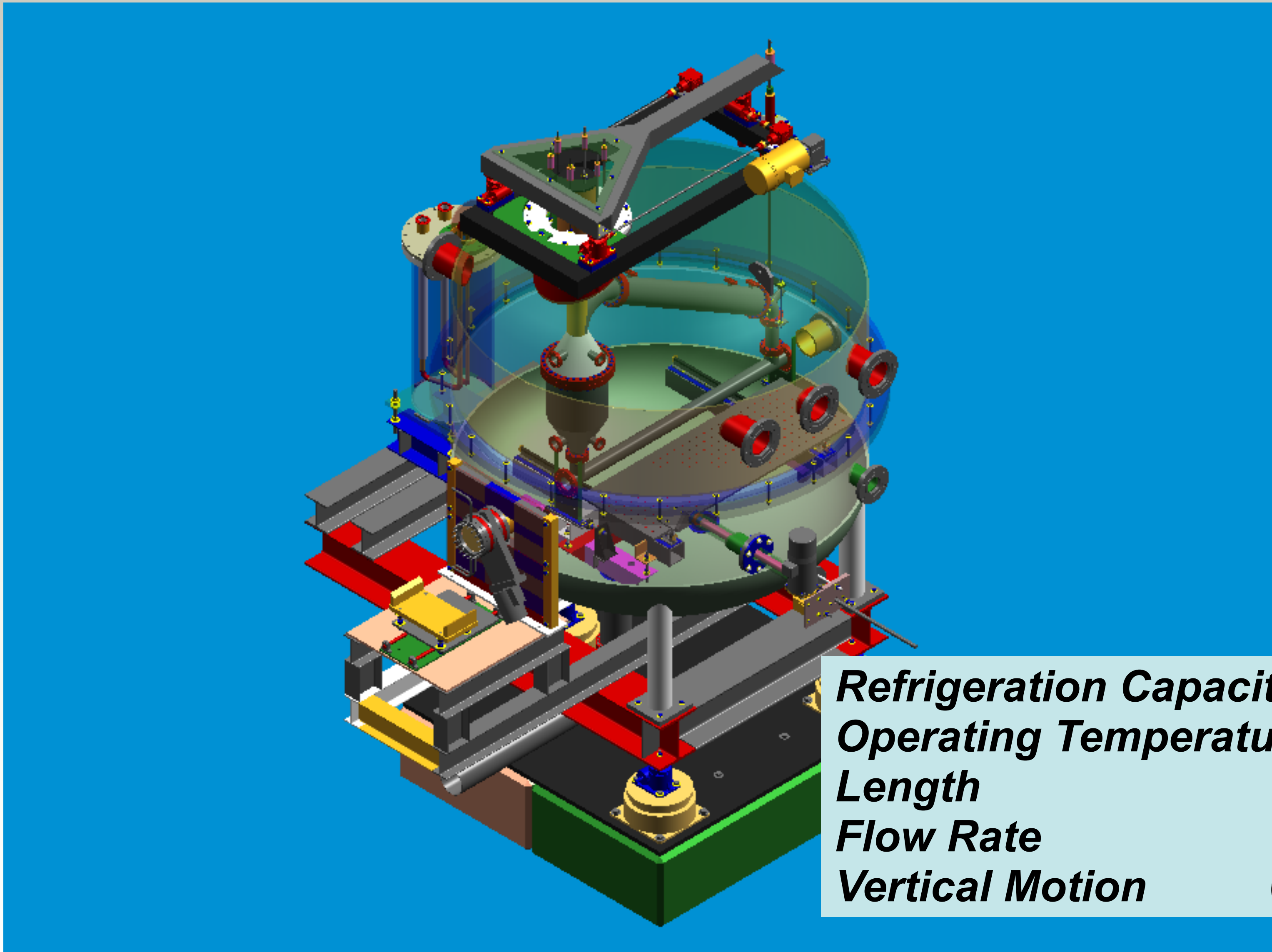
$\sigma_{BPM} \leq$ 2 microns



$\sigma_{toroid} \leq$ 30 ppm

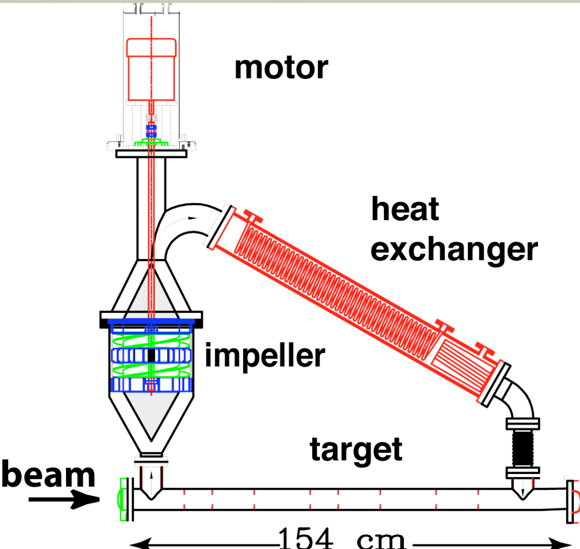


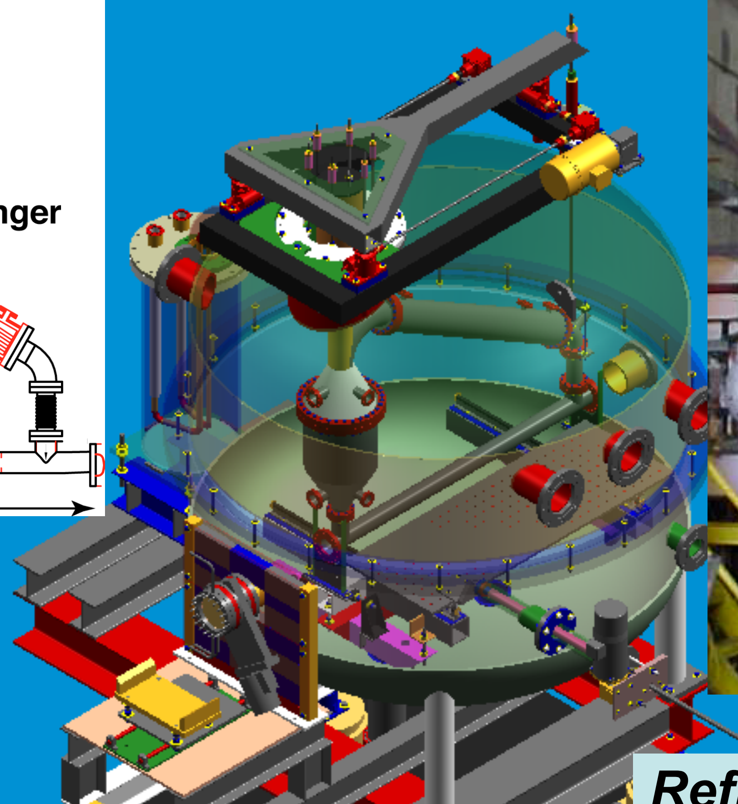
Liquid Hydrogen Target

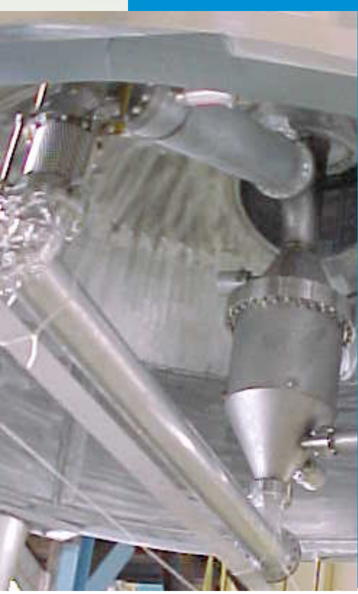


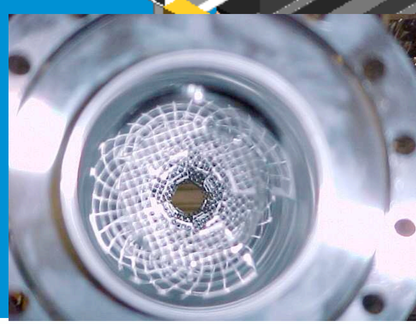
Refrigeration Capacity	700 W
Operating Temperature	20 K
Length	1.5 m
Flow Rate	5 m/s
Vertical Motion	6 inches

Liquid Hydrogen Target





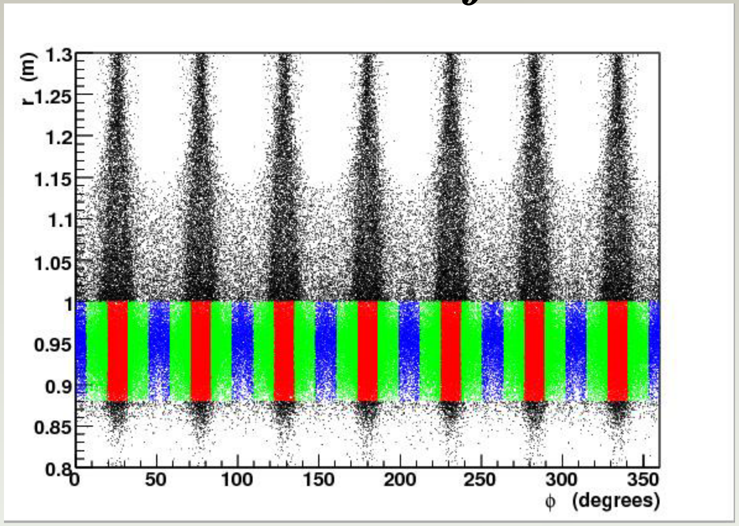


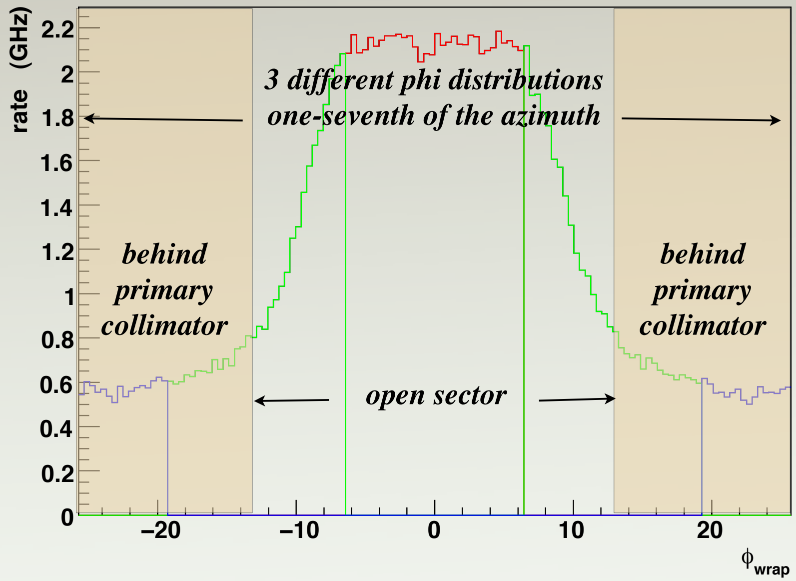


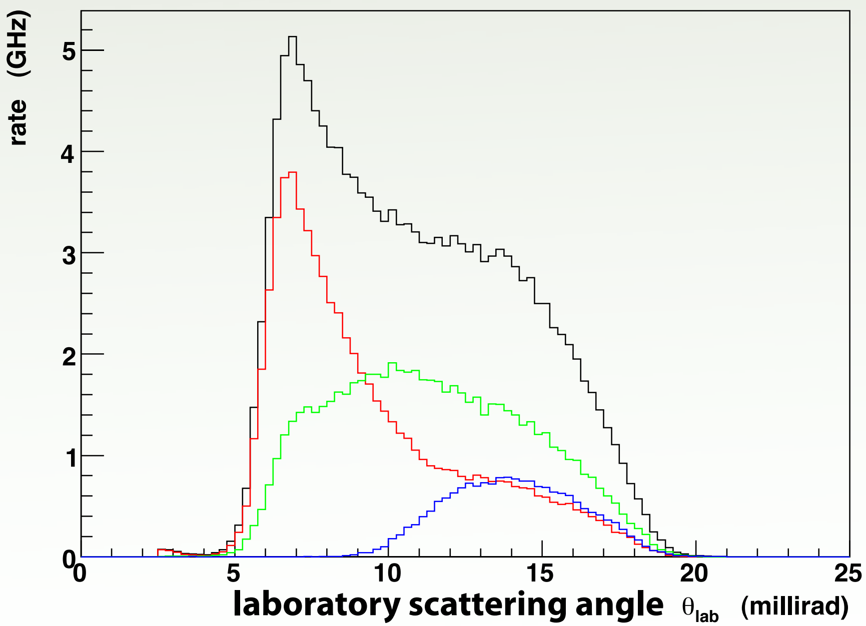
Refrigeration Capacity	*700 W*
Operating Temperature	*20 K*
Length	*1.5 m*
Flow Rate	*5 m/s*
Vertical Motion	*6 inches*

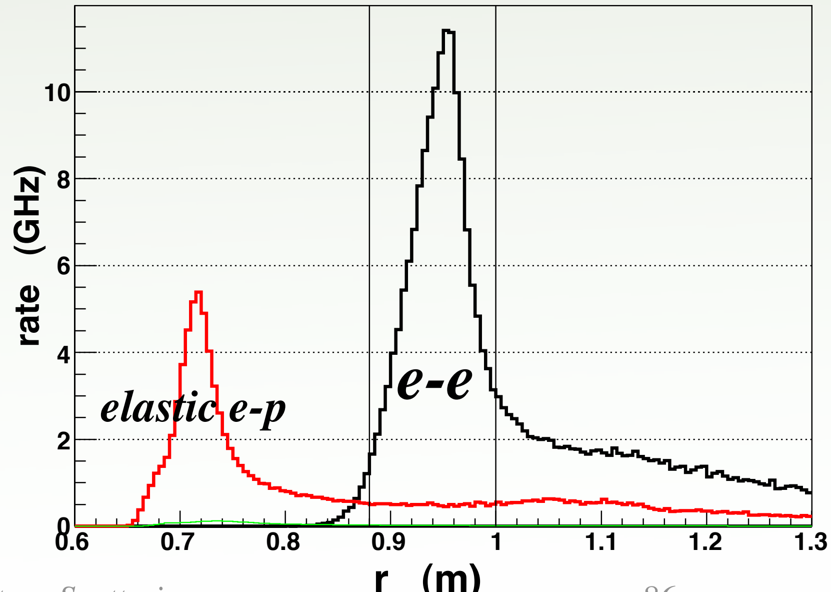
Simulations

Initial and final state radiation effects in target

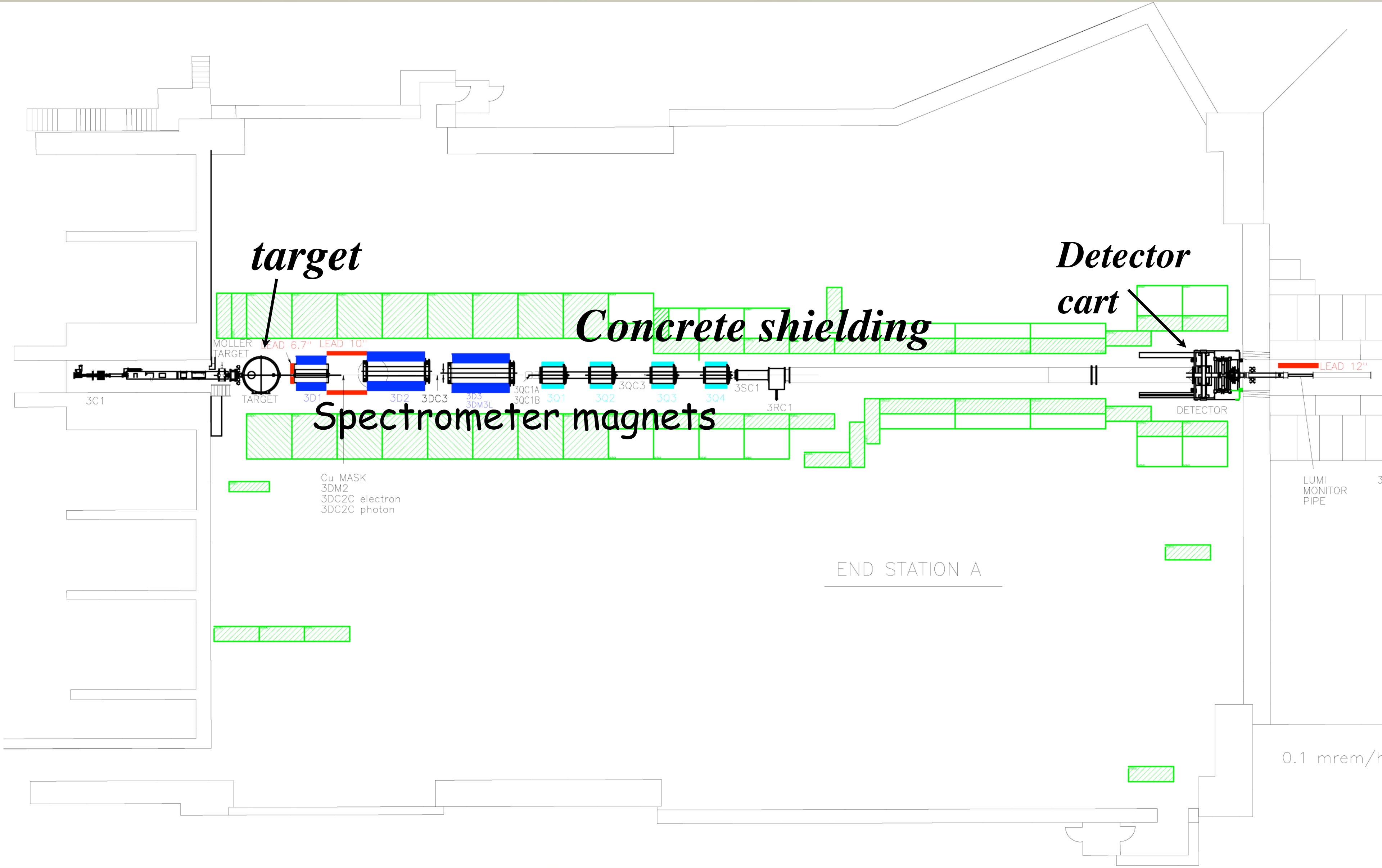




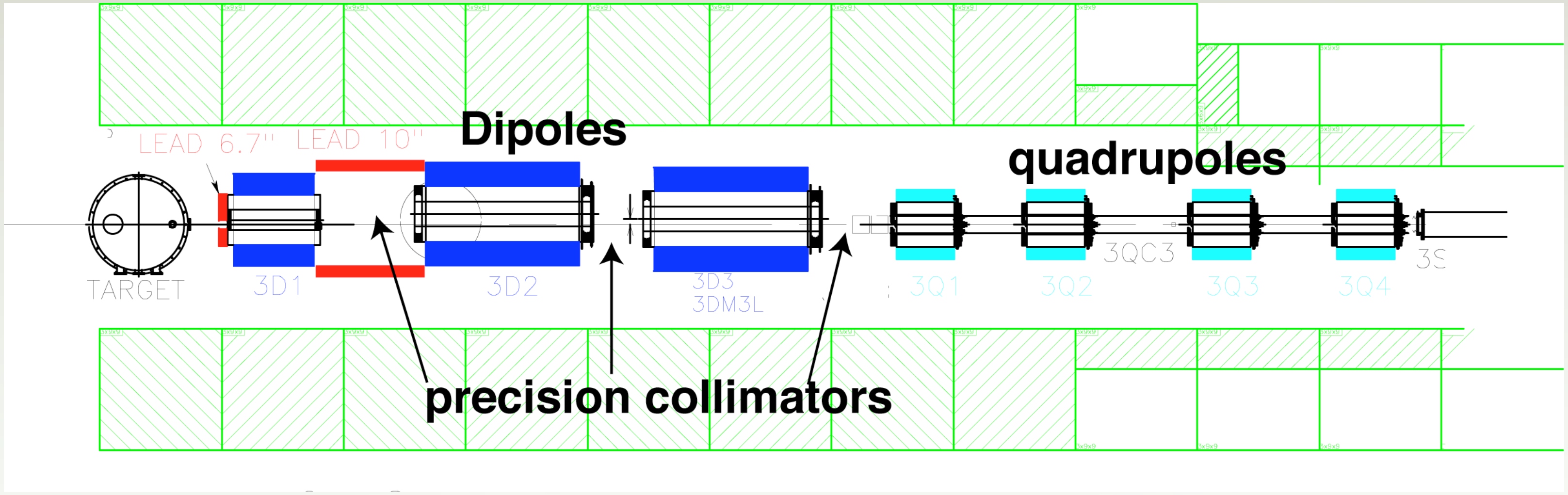




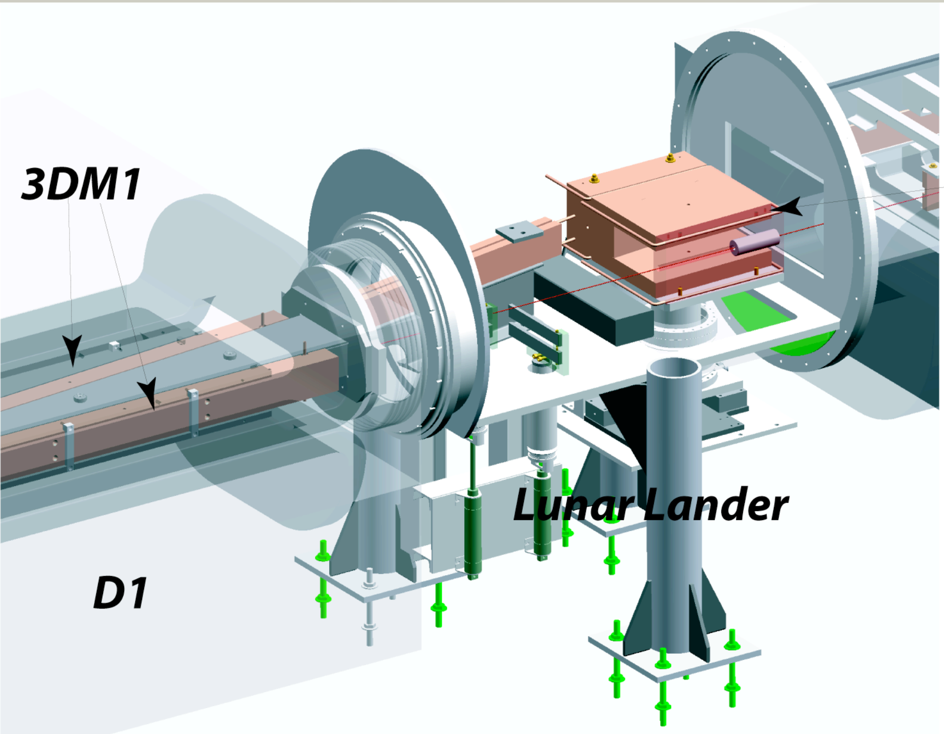
Spectrometer Collimation



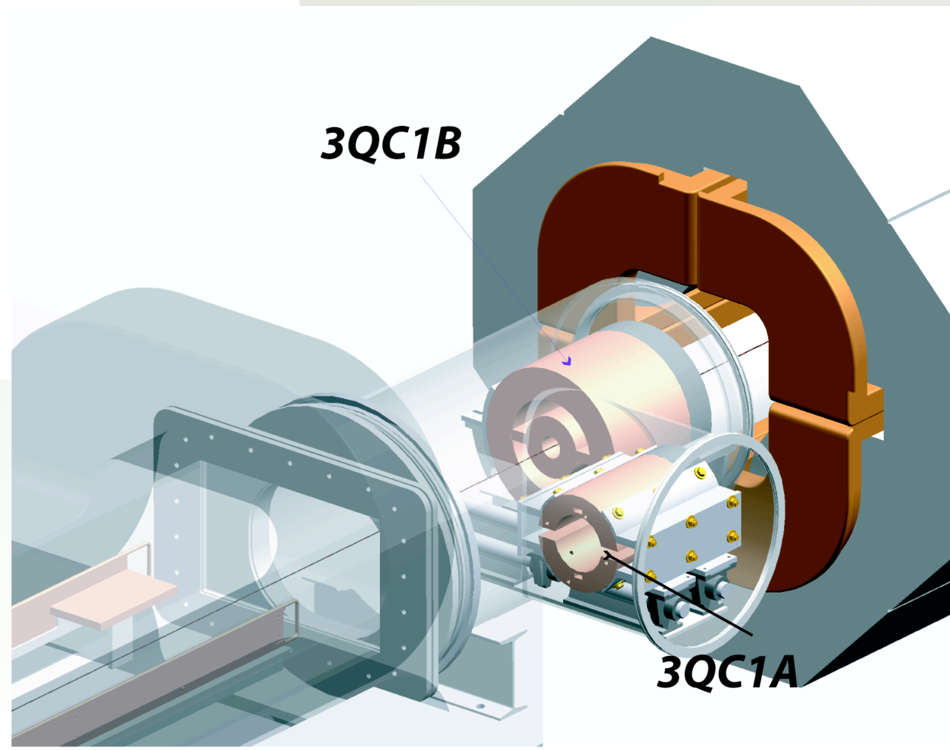
Spectrometer Collimation



Spectrometer Collimation

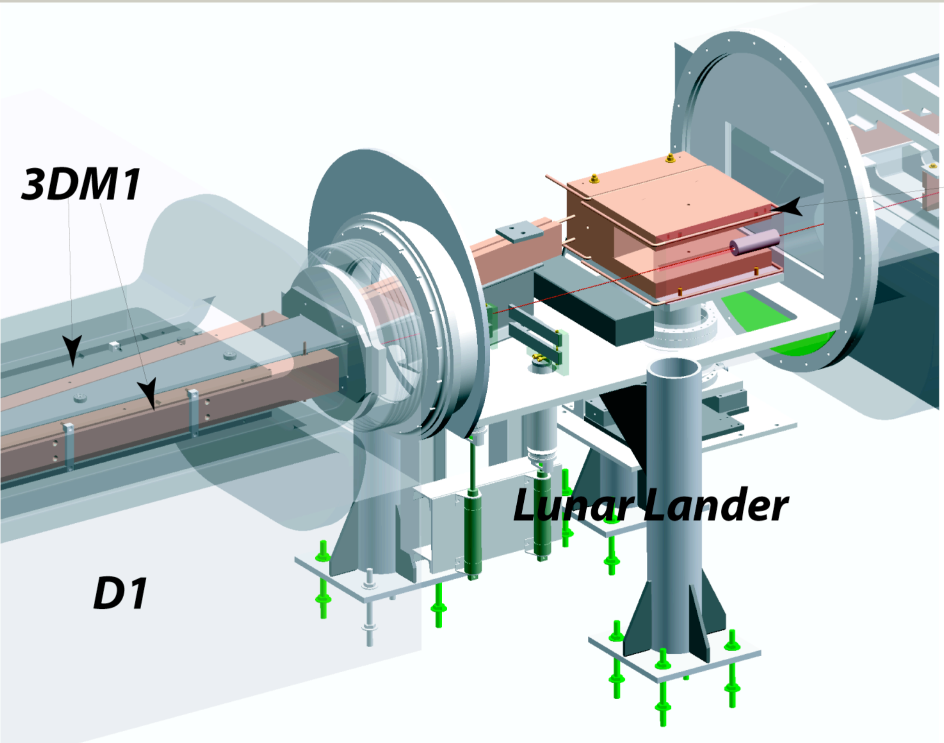


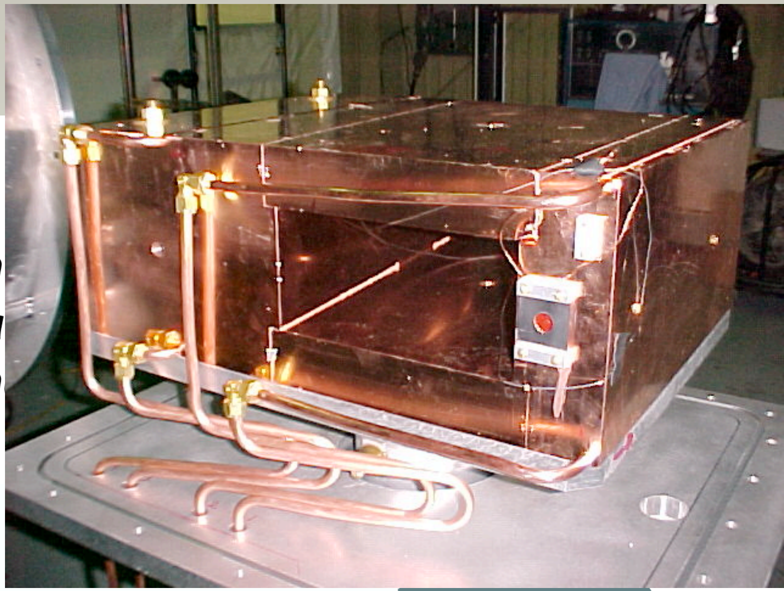
Precision Collimators Critical for the Control of Backgrounds

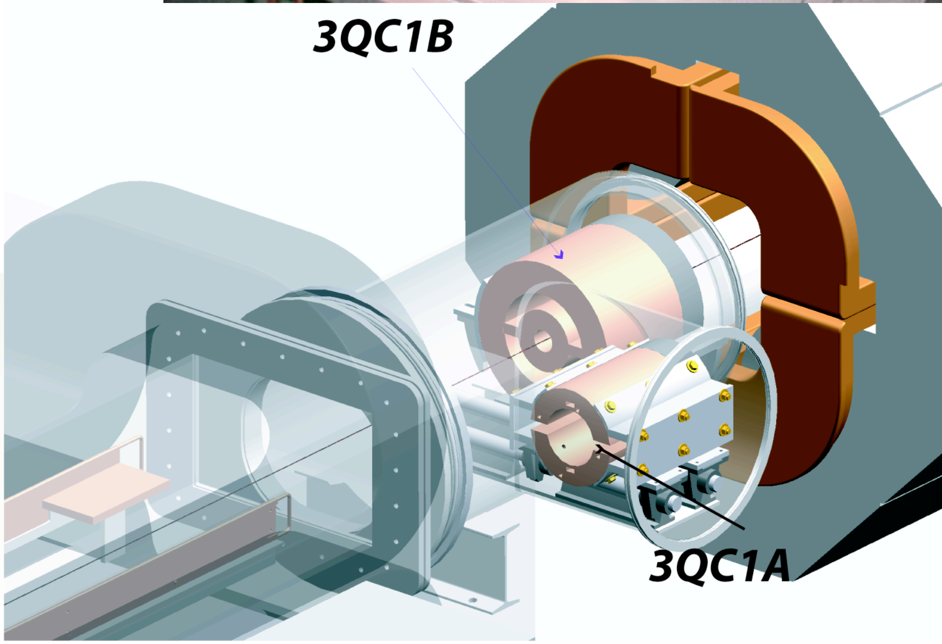


Significant Simulation, Design and Fabrication Effort

Spectrometer Collimation







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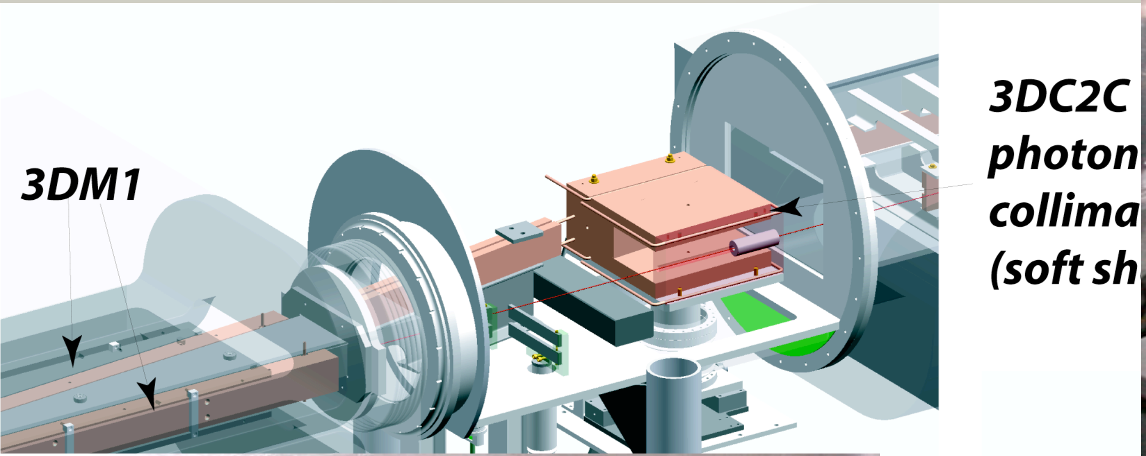
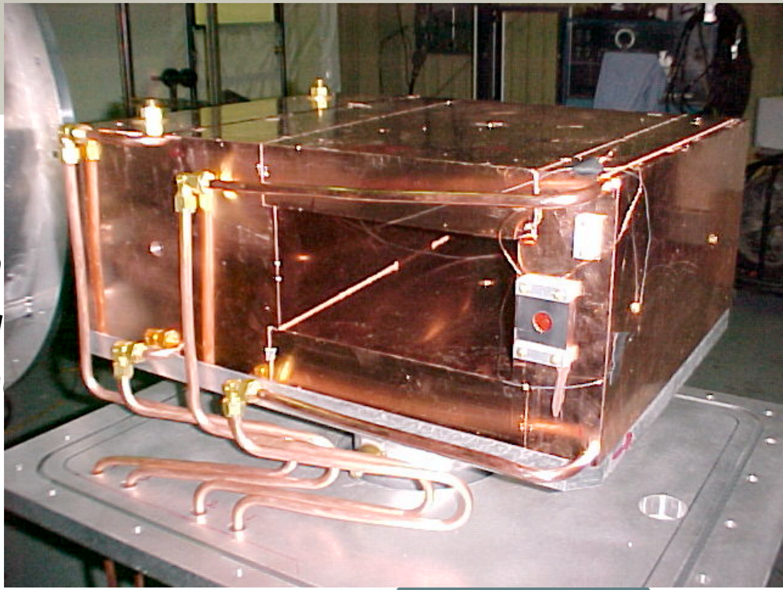
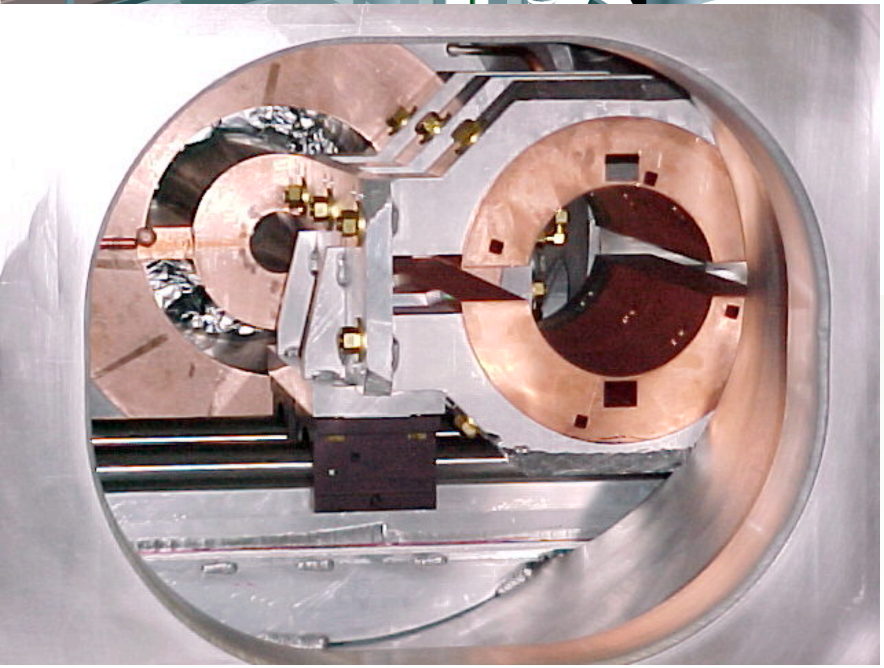
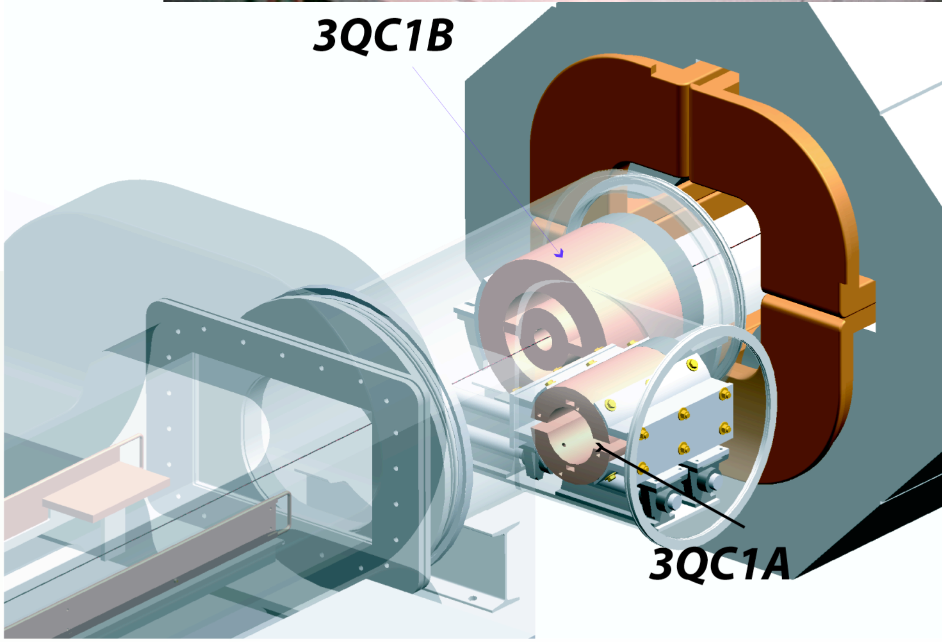
Significant Simulation, Design and Fabrication Effort

Spectrometer Collimation

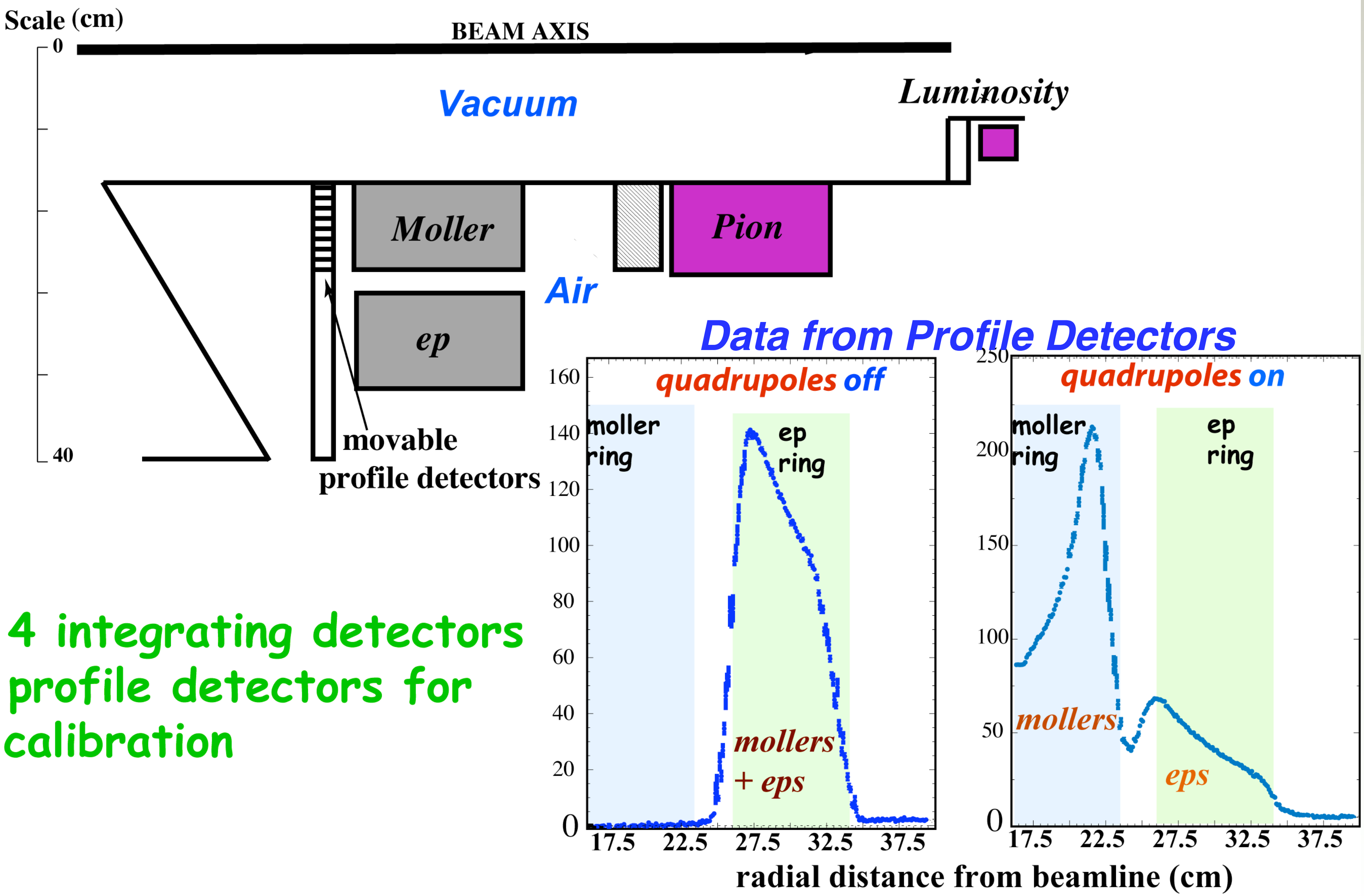








Detector Concept

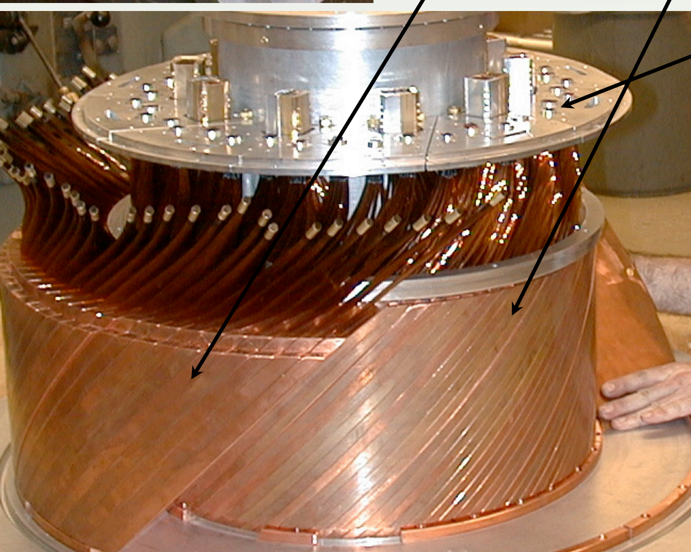


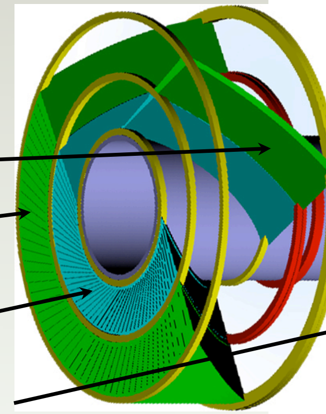
* 4 integrating detectors
* profile detectors for calibration

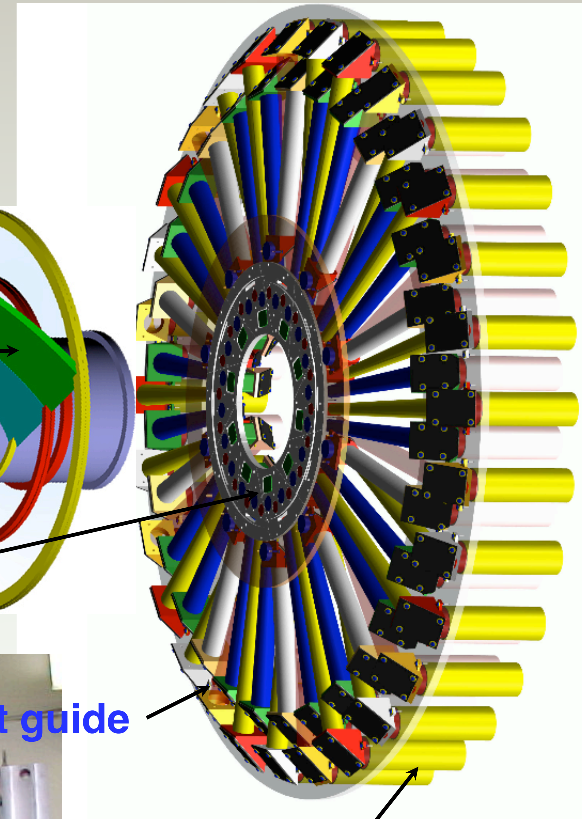
Integrating Calorimeter

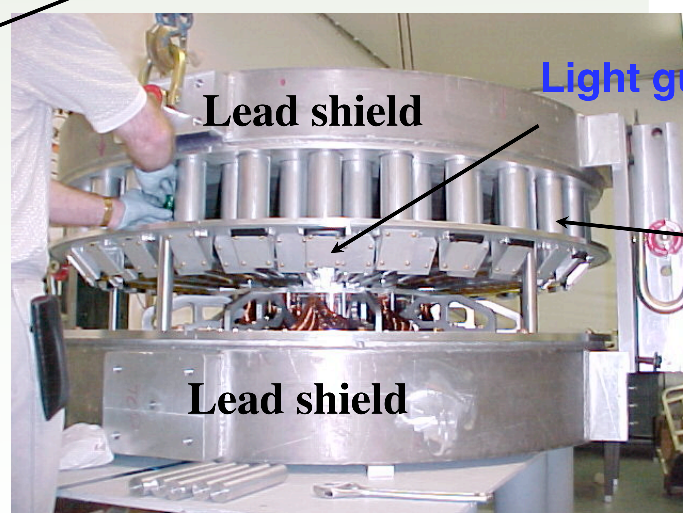
- *20 million 17 GeV electrons per pulse at 120 Hz*
- *100 MRad radiation dose: Cu/Fused Silica Sandwich*

–State of the art in ultra-high flux calorimetry
–Challenging cylindrical geometry

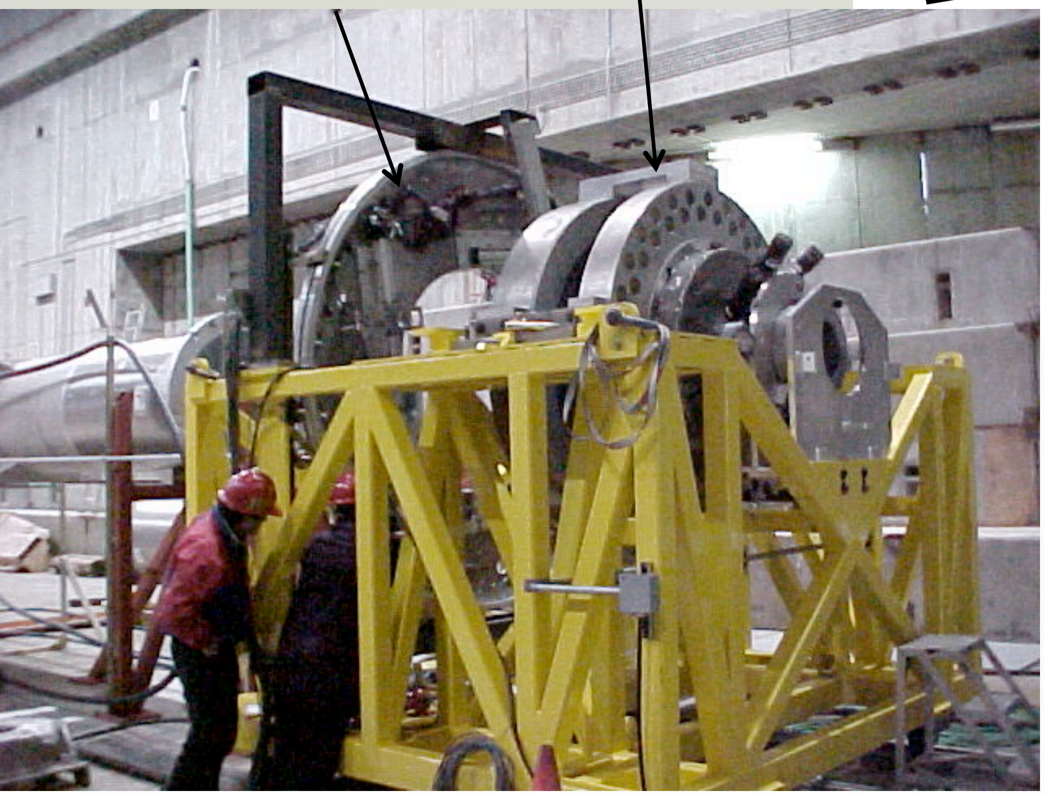


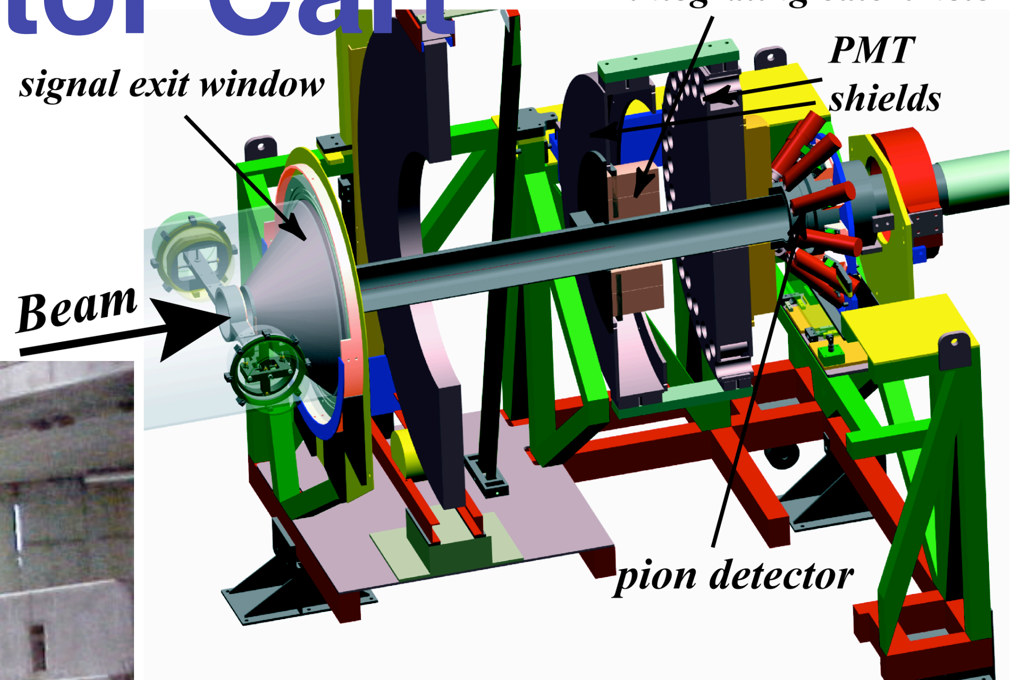


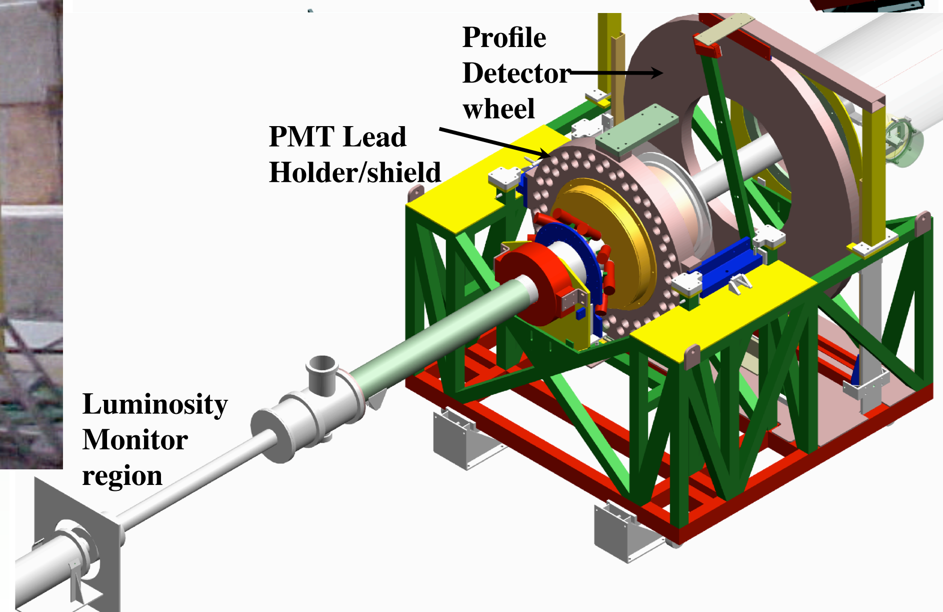




Detector Cart

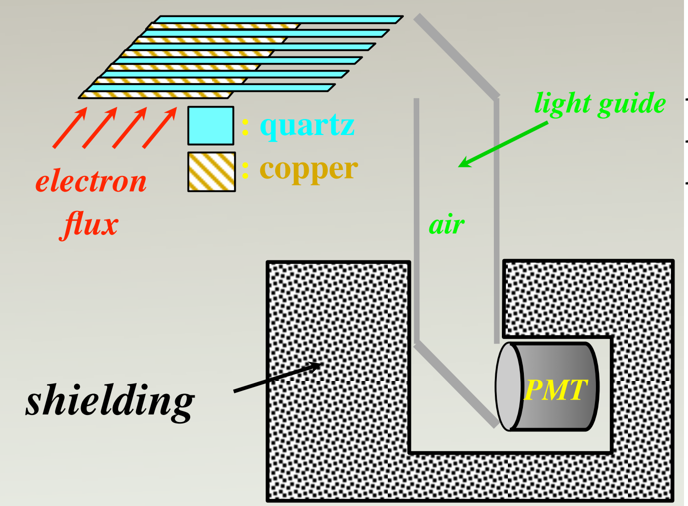




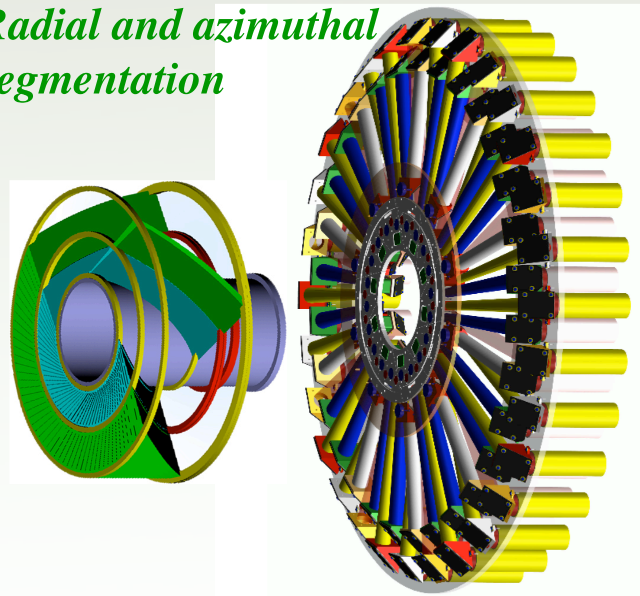


E158 Analysis

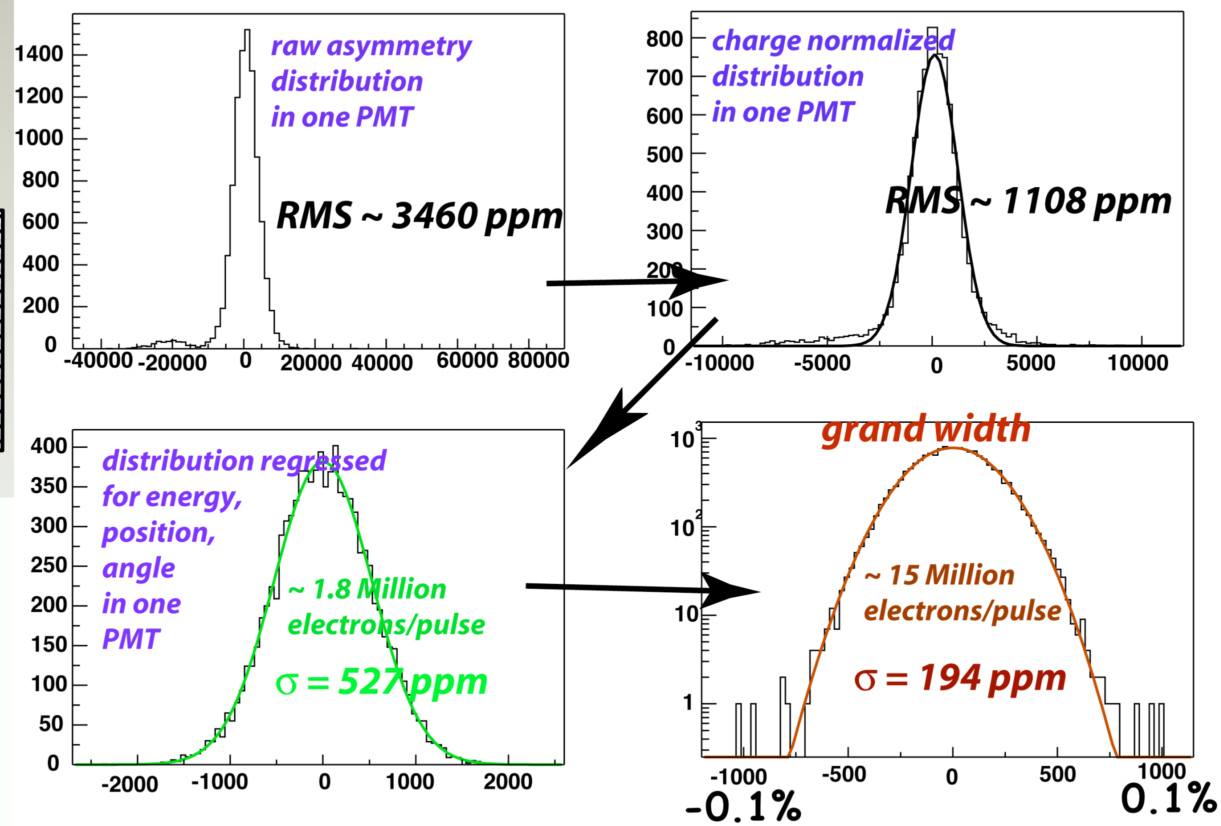
Basic Idea:



Radial and azimuthal segmentation



observed left-right asymmetry distribution



- Corrections for beam fluctuations
- Average over runs
- Statistical tests
- Beam polarization and other normalization